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Corrective Measures for Releases to Ground Water from Solid Waste Management Units

Alliance Technologies Corp., Bedford, MA

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The HSWA of 1984 requires corrective measures for all releases of hazardous waste or hazardous constituents from any solid waste management unit at a treatment, storage or disposal facility seeking a RCRA permit, regardless of the time at which waste was placed in such unit. In this report, ground-water control/treatment technologies ~~and~~ at hydrogeologic settings are identified and assessed.

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SECTION 1

INTRODUCTION

BACKGROUND

The 1984 amendments to the Hazardous and Solid Waste Act (HSWA) provide the Agency with additional authorities for corrective action at facilities seeking permits, and for facilities with interim status under Section 3005(e). The amendments for corrective action address:

- Continuing releases at permitted facilities (Section 206);
- Corrective action beyond facility boundaries (Section 207);
- Financial responsibility for corrective action (Section 208); and
- Interim status corrective action orders (Section 233).

The new authorization allows EPA to require corrective action in response to a release of hazardous waste or hazardous constituents from any solid waste management unit (SWMU) to the environment, regardless of when the waste was placed in such unit. This authority addresses release to all media, including ground water.

Subpart F of 40 CFR Part 264 requires cleanup of ground water at hazardous waste land disposal facilities when hazardous constituents (identified in 40 CFR Part 261, Appendix VIII) are detected in ground-water monitoring wells. As indicated above, Section 206 of the HSWA amendments (Section 3004(u) of the Resource Conservation and Recovery Act (RCRA)) expand these "corrective action" requirements to include ground-water releases from any SWMU.

Based on these 1984 amendments, the U.S. EPA, Office of Solid Waste (OSW), Land Disposal Branch, must develop technical guidance for permit writers to implement the "continuing releases" provision. Implementation of these new requirements will typically take place in three stages: (1) determining whether there is a release at a facility that warrants further investigation, (2) collecting additional information to define the nature and extent of the release, and (3) selecting and performing the corrective measures. The guidance provided in this document will identify mechanisms to correct releases to ground water. A draft document entitled "Phase I Corrective Action Guidance: Information and Methodology for Identifying Releases from Solid Waste Management Units" provides guidance on identifying releases to ground water (Sobotka, 1985).

The remainder of this section, Section 1, identifies and defines the various types of solid waste management units (SWMUs). It also discusses releases to ground water from these units. Section 2 provides an overview of corrective measures including ground-water treatment technologies and mechanisms to intercept or divert ground-water flow. Section 3 discusses case studies where releases to ground water from SWMUs have occurred and identifies the corrective measures undertaken at the site to clean-up the contaminated ground water. Finally, Section 4 provides recommendations for the application of corrective measures to ground-water releases.

DEFINITION/IDENTIFICATION OF SOLID WASTE MANAGEMENT UNITS

Congress defined the term solid waste management unit (SWMU) to include any unit at a facility "from which hazardous constituents might migrate, irrespective of whether the units were intended for the management of solid and/or hazardous wastes". SWMUs represent a broad category of waste management units of which hazardous waste management units are a subset. Under the new requirements, Subtitle D landfills and other units (at facilities seeking a RCRA permit) which primarily handle non-hazardous solid waste could be required to take corrective action if there is evidence of a release of hazardous constituents from these units. The definition of SWMU includes both active, or operating units, and inactive, or non-operating units. This defintion also includes certain units that have previously been exempted from 40 CFR Part 264 requirements, such as wastewater treatment tanks.

The new requirements also extend to spills and other releases from SWMUs that may occur during the normal operation of these units. However, spills that cannot be linked to SWMUs, such as those originating from production areas or product storage tanks, are not covered under the continuing release provision. These spills are illegal, however, under other RCRA provisions (Sobotka, 1985).

The types of units included in the SWMU definition are in alphabetical order:

- container storage areas;
- incinerators;
- injection wells*;
- landfills;
- land treatment units;
- surface impoundments;
- tanks (including 90-day accumulation tanks);
- transfer stations;
- underground injection wells*;
- waste handling areas;
- waste piles;
- waste recycling operations; and
- wastewater treatment tanks.

A container, as defined in 40 CFR Part 260.10, is any portable device in which a material is stored, transported, treated, disposed of or otherwise handled. A container storage area is the location where the container(s) resides. Container storage areas typically consist of 55-gallon drums, but may very in size. These areas usually include a spill containment system, typically a diked area above a low permeable barrier that underlies the storage area, and sometimes include a cover to shed precipitation.

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*Underground injection wells are not discussed in the body of this report; their regulatory status and their potential cause of release to ground water is discussed in Appendix A.

An incinerator, as defined in 40 CFR Part 260.10, is an enclosed device using controlled flame combustion, the primary purpose of which is to thermally break down hazardous waste. Examples of incinerators are rotary kiln, fluidized bed, and liquid injection incinerators.

A landfill, as defined in 40 CFR Part 260.10, is a disposal facility or part of a facility where hazardous waste is placed in or on land and which is not a land treatment facility, a surface impoundment, or an injection well. This facility typically consists of wastes placed on a liner system to collect liquids draining from waste and includes a similar liner system (cover) on top of the waste to prevent incident precipitation from entering the waste.

A land treatment facility, as defined in 40 CFR Part 260.10, is a facility or part of a facility at which hazardous waste is applied onto or incorporated into the soil surface; such facilities are disposal facilities if the waste will remain after closure. Land treatment involves degradation of organic compounds through physiochemical biologic degradation. Nutrient and biological seeding frequently occurs with aeration of the soil/waste mixture by rototilling, plowing or harrowing.

A surface impoundment or impoundment, as defined in 40 CFR Part 260.10, means a facility or part of a facility which is a natural topographic depression, man-made excavation, or diked area formed primarily of earthern materials (although it may be lined with man-made materials), which is designed to hold an accumulation of liquid wastes or wastes containing free liquids, and which is not an injection well. Examples of surface impoundments are holding, storage, settling and aeration pits, ponds and lagoons.

A tank, as defined in 40 CFR Part 260.10, is a stationary device designed to contain an accumulation of hazardous waste which is constructed primarily on non-earthern materials (e.g., wood, concrete, steel, plastic) which provide structural support.

A transfer facility, as defined in 40 CFR Part 260.10, is any transportation related facility including loading docks, parking areas, storage areas and other similar areas where shipments of hazardous waste are held during the normal course of transportation.

Waste handling areas include container filling and emptying areas, and transfer locations (e.g. from trucks to tanks) associated with all waste management facilities. Waste handling areas are usually associated with waste transfer, such as solvent reclamation staging, incineration charging, or transfer from tank truck to tank, or drum storage area to trucks.

A (waste) pile, as defined in 40 CFR Part 260.10, is any non-containerized accumulation of solid, non-flowing hazardous waste that is used for treatment or storage. This facility typically consists of wastes placed on a liner system to collect liquids draining from the waste.

Waste recycling operations are areas where operations involving the processing of waste materials for recovery are undertaken.

A wastewater treatment unit, as defined in 40 CFR Part 260.10, is a device which: (1) is part of a wastewater treatment facility which is subject to regulation under either Section 402 or Section 307(b) of the Clean Water Act; (2) receives and treats or stores an influent wastewater which is a hazardous waste as defined in 40 CFR Part 261.3, or generates and accumulates a wastewater treatment sludge which is a hazardous waste as defined in 40 CFR Part 261.3, or treats or stores a wastewater treatment sludge which is a hazardous waste as defined in 40 CFR Part 261.3; and (3) meets the definition of tank in 40 CFR Part 260.10 (as previously discussed).

IDENTIFYING RELEASES TO GROUND WATER

A release to ground water has occurred when concentrations of hazardous constituents (HCs), defined in 40 CFR Part 261, Appendix VIII, detected at downgradient wells located at the point of compliance (POC) exceed either background constituent levels, the maximum concentrations for parameters in Table 1 of 40 CFR Part 264.94 or some Alternate Concentration Limit (ACL) (Sobotka, 1985). The "Phase I Corrective Action Guidance: Information and Methodology for Identifying Releases from Solid Waste Management Units", draft report (Sobotka, 1985), provides guidance to facility owners or operators on identifying releases to ground water.

All land-based SWMUs (landfills, surface impoundments, waste piles and land treatment units) should be considered as having releases to ground water. This is consistent with 40 CFR 264.70(a) which requires "regulated" units (namely those indicated above) to comply with Subpart F. Other land based units and certain above ground units that contain or have contained hazardous constituents should be considered to be releasing where the existing monitoring system or inspection program is not capable of detecting a release or where there is a ground-water monitoring system in place and background concentrations of hazardous constituents have been exceeded. Other land-based SWMUs subject to ground-water monitoring include: container storage areas without secondary containment; tank systems, including appurtenances (e.g. pipes and valves), without full secondary containment and leak detection systems and which are not fully above the ground; and waste handling areas where discharges have occurred and have not been adequately cleaned up. Categorical exemptions may be made for units that overlie Class III ground waters since they are not considered as a potential source of drinking water and are of limited beneficial use.

Specifically, "direct" ground-water releases from SWMUs occur primarily as a result of poor design and operating practices. General categories which the applicant should have addressed include but are not limited to:

- inadequate QA/QC procedures used during construction and operation of the SWMU;
- insufficient hydrogeologic investigations;
- improper foundation preparation prior to liner system installation;
- inadequate design of liner, leachate collection and leak detection systems; and
- inadequate secondary containment and runon/runoff control systems.

Although the above design and operating practies should be considered for all types of SWMUs, they are of particular importance to land-based SWMUs such as landfills, surface impoundments, waste piles and land treatment units. During and following liner system construction, strict QA/QC procedures should be adhered to to ensure that no nonuniformities, damage or imperfections (including inadequate liner seams) exist in the liner system (i.e., synthetic and clay liners, leachate collection and leak detection systems) which could result in failure and subsequent release of hazardous constituents.

Additionally, prior to liner system installation, particularly for synthetic liners, the foundation, or bedding layer should be smooth, uniform and free of holes, cracks or pretruding debris which could result in increased hydraulic conductivity. In designing liner, leachate collection and leak detection systems these systems must be capable of withstanding waste loading, be compatible with hazardous constituents, prevent migration of hazardous constituents, and withstand physical, chemical and biological attack. Inadequate design of any of these factors could result in hazardous constituent release.

Hydrogeologic investigations should provide complete and detailed information on subsurface characteristics, for example, fault locations, depth to bedrock, water table and perched or confined aquifer locations, and potential hazardous constituent transport pathways in the event of a release. Hydrogeologic investigations are also essential to ensure that after installation of a SWMU the facility will not fail (structurally) as a result of subsurface movement due to overburden pressures.

"Indirect" releases to ground water from SWMUs occur as a result of releases to soil and/or surface water that through, for example, percolation make their way to ground water, thereby causing contamination. These releases are due to unpermitted point source discharges, spills, leaks, or surface or subsurface (unsaturated zone) run-off.

Certain unsound design and operating practices will allow waste to migrate from the SWMU and possibly mix with run-off. Examples include surface impoundments with insufficient freeboard that do not prevent periodic overtopping, and leaking tanks or containers. In addition, precipitation falling on exposed wastes can dissolve or transport hazardous constituents. For example, at typical uncapped active or inactive waste piles and landfills precipitation and leachate are likely to mix at the toe of the active face or the low point of the trench floor. Design and operating practices which could result in "indirect" releases to ground water from SWMUs are discussed below. For further discussion on indirect releases refer to the following draft reports: "Corrective Measures for Releases to Surface Water", August 1985, prepared by E.C. Jordan Co. under subcontract to GCA/Technology Division; and, "Corrective Measures for Releases to Soil from Solid Waste Management Units", August 1985, prepared by GCA/Technology Division.

Container Storage Areas

Potential releases may occur due to failure to include a spill containment structure; inappropriate separation of incident precipitation and spill residue; accidental spills during operation; and corrosion of containers. The presence of leaking containers or liquids increases the possibility of a current or future release from these units. Leaking containers allow uncontained run-off to mix with and transport hazardous waste. Uncontained run-off may lead to either soil, ground water, or surface water contamination.

Incinerators

In addition to releases associated with waste handling tanks and container storage facilities releases may occur as a result of residue quenching water releases and stack emission control effluent.

Landfills and Waste Piles

Typical releases may be from inadequate control of run-on and incident precipitation resulting in contaminated surface runoff from the facility, if the water comes in contact with the waste and carries dissolved or suspended waste solids. A failed leachate collection/removal system may also result in indirect releases to ground water through indirect release to surface water through seeps. In addition, a failed cover or liner system may result in seeps.

Land Treatment Units

Releases occur primarily from run-on and incident precipitation. Secondary releases that may affect stream water quality and subsequently affect ground water include air blown solids, evaporation and recondensation of volatiles or semivolatiles.

Surface Impoundments

Surface impoundments with inadequate freeboard may result in overtoppin because of wave action during storm events. Earth dikes which are not structurally sound may result in releases through cracks and leaks. The lack of either grass, rip rap (rock) or other protection on dikes may contribute to future releases because of erosion resulting from exposure to wind and water.

Tanks

Release of hazardous constituents from tanks may occur as a result of leaks or overflow. Leaks can occur due to cracks or structural failure. Corrosion caused by waste/construction material or soils can contribute to inadequate structural integrity of tanks. In addition, faulty valves or pipe connections or open valves may result in release of hazardous constituents. Operational failure may result in tank overflow. lack of a secondary containment system further increases the risk of release to the environment.

Waste Handling Areas

Typical releases occur as a result of recurring spills (of limited volume), and surface runoff flushing contaminated surfaces (soil, concrete, spill containment structures).

Tables 1.1 and 1.2 summarize design and operating practices associated with direct and indirect releases to ground water from SWMUs.

TABLE 1.1 CAUSES OF DIRECT GROUND-WATER RELEASES*

Design Practices
Inadequate QA/QC procedures used during construction
Insufficient hydrogeologic investigations
Improper foundation preparation prior to liner system installation
Inadequate design of liner, leachate collection and leak detection systems
Operational Practices
Inadequate QA/QC procedures used during operation of SWMU

*Applicable to landfills, surface impoundments and waste piles.

TABLE 1.2. CAUSES OF INDIRECT GROUND-WATER RELEASES*

Design and Operating Practices	Applicable SWMUs
Design Practices	
Insufficient cover	Surface impoundments, waste piles, landfills
Inadequate freeboard (runon/runoff control)	Surface impoundments
Presence of liquids or waste exposed to environment	Surface impoundments, waste piles, landfills, land treatment units
Location of a SWMU near a surface water body	Surface impoundments, waste piles, landfills, land treatment units
Inadequate secondary containment and runon/runoff control	Waste piles, landfills, land treatment units, container storage areas, tanks, waste handling areas
Operational Practices	
Operational failure, faulty piping or other occurances resulting in leaks and spills	Tanks, container storage areas, waste handling areas
Cracks or structural failure in dike walls or tanks	Surface impoundments, landfills, container storage areas, tanks
Lack of protection from dike wall erosion or tank corrosion	Surface impoundments, landfills, tanks, container storage areas
Repair, installation or replacement of any primary or secondary containment system while the unit contains waste	All SWMUs
Inadequate QA/QC procedures used during operation of SWMU	All SWMUs

SECTION 2

OVERVIEW OF CORRECTIVE MEASURES FOR RELEASES TO GROUND WATER

GENERAL

As previously indicated, the Hazardous and Solid Waste Act Amendments of 1984 require corrective measures for all releases of hazardous waste or hazardous constituents from any solid waste managment unit (SWMU) at a treatment, storage or disposal facility seeking a RCRA permit, regardless of the time at which waste was placed in such unit.

Corrective measures for releases to ground water involve possible upgradient diversion, downgradient diversion/interception, and extraction/recharge of ground water for certain hydrologic configurations and the assessment of treatment technologies to remove hazardous constituents or to treat them in place. In this section, ground-water control/treatment technologies and hydrogeologic settings are identified and assessed. From these assessments and from the evaluation of case studies (Section 3) on corrective measures implemented for clean-up of hazardous constituent releases to ground water, the relative success or failure of each technology can be determined for various hydrogeologic settings and waste types. Knowledge of relative successes or failures provides the permit writer and the permit applicant with guidance to determine the most appropriate corrective measures for implementation at the site in question.

However, prior to selection of a corrective measure or set of corrective measures, the nature and extent of release, and the need for such meaures must be adequately assessed. Only after the need for corrective measures has been defined can appropriate reliable, effective, and cost-efficient corrective measures be selected. The assessment of need will address such factors as source characterization, transport mechanisms, receptor identification and risk assessment. Depending on the outcome of the needs assessment, corrective measures including source control and/or offsite containment and recovery, and control/treatment technologies may be implemented

Assessing Need for Corrective Measures

As stated previously a corrective measures for ground-water release is required when concentrations of HCs measured at the point of compliance, exceed either background constituent levels, the maximum concentration for parameters in Table 1 of 40 CFR Part 264.94 or some Alternate Concentration Limit. When corrective measures are required, an assessment should first be made to define site conditions and the extent of containment release, to identify the goal of corrective measures, to assist in the selection of corrective measures, and to establish a time frame for implementation of corrective measures. An assessment of the need for corrective measures should include the following: source characterization; hazardous constituent distribution; fate and transport mechanisms; hazard assessment; receptor identification; and risk assessment. These assessment factors are discussed below.

Source Characterization--

The first step in the assessment of need is source characterization. Source characterization involves identifying volumes and concentrations of hazardous constituents present, and the physical and chemical characteristics of the hazardous constituents.

Identification of hazardous constituents may be a relatively simple matter of reviewing records of the solid waste management unit (SMWU) or may require test pits and borings, sampling of soil, sediments, ground water and surface water, and chemical analysis. The identification process should include estimates of the volume of each hazardous constituent and its location both onsite and offsite. Once identified, similar hazardous constituents should be grouped by chemical type and similarity in metabolic or environmental fate.

The physical and chemical characteristics of concern include mobility, bioaccumulation potential, degradation (persistence) and any special characteristics (explosivity or flammability). Mobility of chemicals is primarily related to the solubility, volatility, adsorbability, partition coefficients, and density of the chemicals. Hazardous constituent mobility is important in assessing the risk associated with a particular site. The bioaccumulation and degradation potential also relate to the risk associated with the chemicals released from a site.

Special characteristics of the chemicals must also be considered. Chemicals may also react with soils thereby either increasing or decreasing the physical properties of the soil, most notably permeability. The potential for chemical interactions should also be considered. Chemical-to-chemical or waste-to-waste interactions may affect mobility, reactivity, solubility, or toxicity of the chemicals. The potential for wastes or reactive products to interact with containment materials should also be considered.

Transport Mechanisms--

Hazardous constituents may be transported in ground waters intact, in a dissolved state, as colloids or particulates, or adsorbed to sediment. The method by which hazardous constituents are transported to and in ground waters is important in evaluating the risk associated with a release. The transport mechanism aids in identifying media contaminated or likely to be contaminated, the fate of hazardous constituents in the environment and receptors likely to be affected, and the effectiveness of corrective measures.

Receptor Identification--

Receptor identification is an important part of determining the need for implementing corrective measures and the time frame within which implementation should occur. Receptor identification will be related to hazardous constituent characteristics and transport mechanisms. Receptors should be identified by type, location, number of receptors and any special characteristics.

The type of receptor most likely to be affected by releases to ground water include drinking water supplies. Water supplies may be contaminated directly by release of hazardous constituents to ground-water supply sources or indirectly when contaminated surface waters and soils contaminate ground-water supplies. When water supplies are affected, applicable water quality standards should be considered. When chemicals for which there are no established standards are present, the toxicity of the chemicals must be considered.

The distance between the source and the receptor affects the time until exposure occurs and the effective concentration of hazardous constituents at exposure. The persistence and fate of the chemicals during transport over this distance affects the concentration of the chemicals at the receptor. Additionally, the number of receptors or individuals and any sensitive populations that may be present should be considered in establishing the need for corrective measures.

Hazard and Risk Assessment--

The need for corrective measures should be based on the risk the release presents to human health and the environment. The risk is determined based on an exposure assessment and a hazard assessment. The exposure assessment is a function of the duration of exposure and concentration of chemicals over that time. The hazard assessment evaluates toxic, chronic and carcinogenic/mutagenic effects of the concentration of chemicals. Hazards may be assessed by reference to ambient water quality criteria (AWQC), National Interim Primary Drinking Water (NIPDW) regulations, state water quality standards and health advisories, and Allowable Daily Intake (ADI) values. Where such criteria are not available, the hazard of chemicals should be assessed based on available scientific data.

HYDROGEOLOGIC APPROACHES

General Introduction

Ground-water contamination may result from the generation of leachate which is defined under RCRA as "any liquid, including any suspended components in the liquid, that has percolated through or drained from hazardous wastes"

(Federal Register 45, 33075, May 19, 1980) or from a hazardous constituent spill entering the saturated zone. Ground-water contamination may occur at a wide variety of SWMUs such as landfills and surface impoundments.

Corrective measures include both: (1) control measures which temporarily abate hazardous constituent release by interrupting constituent transport, and (2) removal or treatment techniques which permanently remediate the release. Such corrective measures include the following:

Control Measures	Removal/Treatment Techniques
source control	source removal
upgradient ground-water diversion	downgradient ground-water interception and treatment
	extraction/recharge
	in situ treatment

As per 40 CFR Part 264.100(b), if hazardous constituents from a regulated unit exceed the ground-water protection standard established for the regulated unit then the owner or operator must have a corrective action program designed to bring the unit back into compliance with the standards. A corrective action program to achieve compliance with the ground-water protection standard must be achieved by removing the hazardous constituents or treating them in place. That is, ground water can be protected by preventing the generation of hazardous waste leachate, where feasible, and by removing such leachate from the subsurface environment when it appears. Measures which only prevent the migration of hazardous constituents in the ground water for some period of time do not provide an adequate level of ground-water protection and must, therefore, be supplemented with additional remedial measures.

Source control methods prevent or reduce the potential for hazardous constituent release and thus, migration into the ground water. This might include, for example, excavation of contaminated soil and reduction of surface infiltration. Upgradient diversions or barriers are control meaures which prevent ground water from contacting the waste mass or the hazardous constituent plume by rerouting the ground-water flow pattern and adjusting the level of the water table. These control measures, as stated in 40 CFR Part 264.100(b) must be combined with other remedial meaures, such as counterpumping, to constitute an adequate corrective action program. Downgradient diversions/interceptions are barriers to intercept, prevent and contain the flow of contaminated ground water and subsequently pump or direct it to a discharge where it can be treated or disposed of under satisfactorily controlled condtions (EPA, 1983). Extraction/recharge involves the extraction and treatment of contaminated ground water and the subsequent recharge of the treated ground water into the source aquifer. In situ treatment involves the direct treatment of contaminated ground water in place. Although an emerging technique, it is believed, as per 40 CFR Part 264.100(b), that the in situ treatment of hazardous constituents is analogous to removal because it provides long-term protection of human health and the environment.

Within each of these corrective measure approaches or strategies, several technologies exist which may be either proven, imminent, or emerging; proven being conventional and demonstrated, imminent being in a developmental stage, and emerging being in a conceptual phase. Control technologies for the source control strategy are only briefly discussed in this document since guidance is being specifically directed toward corrective actions for releases to ground water. The discussions on ground-water control and treatment technologies identify technical considerations such as site applicability, implementability, advantages and disadvantages, hazardous constituent applicability, reliability, effectiveness, safety, cost, and hydrologic parameters such as pump rate, placement and permeability. Institutional issues are also addressed, where applicable. In viewing permit applications, the permit writer muct be aware of state laws so that institutional issues, for example, the reinjection of treated ground water not being permitted in certain states, can be addressed.

Environmental Considerations

Environmental issues resulting from the implementation of a control/treatment technology also requires consideration. For the majority of the control/treatment technologies presented in this document the environmental considerations arising from "pump and treatment" corrective actions include: (1) subsidence, (2)decrease in well yield of adjacent well fields, (3) drawdown of adjacent surface water bodies, and (4) induced hazardous constituent migration to new pathways.

As ground water is withdrawn from a pumping well, the withdrawal rate typically exceeds the recharge rate to the aquifer initially. In this case, a cone of depression forms around the well in response to Darcy's law. The potentiometric surface steepens around the well, forming the cone of depression, and thereby increases the hydraulic gradient, in order to satisfy the stress imposed on the aquifer by the pumping well. The cone of depression will continue to expand until a new equilibrium is reached when the ground-water withdrawal rate is balanced by recharge. The size of the cone of depression at a given time is a function of the pumping rate and the permeability of the aquifer. Expanding cones of depression and excessive ground-water withdrawals are both potential causes of environmental problems under the circumstances described below.

In an aquifer that contains more than one well screened within it, it is possible for the radii of influence of these wells to expand and intersect when they are being pumped simultaneously. In confined aquifers, the law of superposition can be applied, and the total drawdown effect in the aquifer at a point is the sum of the individual drawdown effects from each participating well at that point. This can lead to a rapid, unexpected decline in the potentiometric surface.

Similarly, in unconfined conditions, cones of depression can intersect surface water bodies such as streams or lakes. This can result in a decline of the water table to a point beneath the water body. In extreme cases, a reversal in the hydraulic gradient can occur, which can ultimately cause complete dewatering of the surface water body. In the case where the pumping rate is adjusted to balance (or be less than) the recharge rate to the water body, there are other potential problems which must be considered. For example, if the aquifer is sufficiently permeable, any detrimental constitutents in the water body might not be attenuated enroute to the well, and may therefore contaminate it. In a similar manner, if the cone of depression reaches a source of hazardous constituents, induced migration of the hazardous constituents within the capture zone of the well will cause them to move toward the well.

In coastal areas, fresh ground water is in hydrodynamic equilibrium with the denser sea water beneath it. The ground water discharges to the sea at an outflow face above the fresh water-sea water interface. However, if significant ground water withdrawals occur in coastal areas, a reversal of the hydraulic gradient can occur, thereby causing an inland shift in the interface such that sea water enters the wells. This process is known as sea water intrusion. Likewise, in non-coastal areas where brackish or saline water is located beneath a fresh ground-water supply, pumping of the ground water can cause upconing of the interface and lead to saline water intrusion.

A final environmental concern due to ground water withdrawal is subsidence. If ground water is displaced from the interstices of the sediments at a rate greater than the recharge rate to the aquifer, then an equal volume of land subsidence occurs due to aquifer consolidation. The fine-grained sediments in the aquitards surrounding an aquifer will also respond to the pumping by induced infiltration. Consequently, aquitard consolidation also occurs. Clays and silts are more compressible than sands and gravels and therefore, the majority of consolidation is primarily due to, but not limited to, aquitard consolidation.

The ability to reverse this process by artificial recharge is quite limited due to the inelasticity of the sediments. Further, since the hydraulic conductivity of a typical aquitard can be several orders of magnitude smaller than an aquifer, consolidation in the aquitard can proceed quite slowly and even continue after pumping is terminated.

Subsidence is a function of aquifer thickness, the structure of the aquifer sediments, aquifer compressibility, the vertical hydraulic conductivity of the media, and the time and extent of the decline in the potentiometric surface. For the case of many pumping wells in one aquifer, the total subsidence is the sum of the consolidation caused by each individual well. Subsidence can cause drastic changes in land surface elevation. The differential setting that ultimately occurs can, for example, destroy wells, foundations, buildings, bridges, and landscapes.

Source Control Technologies

Releases to ground water may originate from a variety of solid waste management units (SWMUs). When a release to ground water has occurred, part of the corrective measures which may be employed will be directed at source control. Source control corrective measures may be used to prevent additional releases by containing hazardous constituents or by removing them from the site.

Removal--

Preventing additional releases from a site can be accomplished by removing all wastes and contaminated media. Removal may involve emptying and removal of tanks, repacking and removal of drums, pumping surface impoundments, and excavating contaminated soils and structures. Removed materials should be transported to an approved facility for treatment or redisposal. The main advantage of removal is that the source of releases is eliminated. A significant disadvantage is the cost of excavation, transportation and redisposal, and the potential risks posed by these activities.

Grading--

Grading refers to actions which are used to alter the topography and runoff characteristics of a waste site. Grading includes excavation, spreading, compaction, scarification, tracking, and contour furrowing. These activities are accomplished with heavy earth-moving equipment (dozers, loaders, scrapers, compactors). Grading has two primary purposes, slope optimization and preparation for revegetation. Slope optimization may include excavation, spreading, compaction and hauling in order to increase surface runoff and decrease infiltration and ponding without increasing erosion. This type of action is designed to prevent surface runoff from contacting waste. Scarification, tracking and contour furrowing are all grading techniques employed to roughen soils to facilitate revegetation. These methods slow runoff thereby increasing infiltration and decreasing erosion potential. Preparation for revegetation techniques are most commonly associated with capping and diversion operations, as well as slope grading.

Grading operations for slope optimization and revegetation may be incompatible with sites with steep topography. Local climatic conditions and soil types will dictate the optimum slopes. Grading equipment and equipment operators are readily available in most locations and grading techniques are well established.

Surface Seals--

Caps, covers and surface seals refer to low permeable barriers which are installed over waste disposal sites. Surface seals may be constructed from a variety of low permeable materials including soils, admixtures (asphaltic concrete, soil cement bentonite), and synthetic geomembranes. Clays and synthetic geomembranes are the materials most often used. Seals reduce the likelihood of releases from waste disposal sites by reducing surface water infiltration and erosion. Surface seals also provide a media suitable for revegetation. Seals are commonly used in conjunction with grading, diversions, and revegetation.

Surface seals are most commonly used for closure operations at permitted disposal sites (e.g., landfills, surface impoundments, waste piles, land treatment units). They are also an appropriate corrective measure for use at uncontrolled sites or where hazardous constituents are present in soils. The main limitation of surface seals is the need for slope control and maintenance.

Diversion and Collection--

Ground water releases can also be controlled by the management of surface waters. By routing surface runoff away from a site, thereby preventing run-on, direct contact with waste and precipitation is reduced. Because the majority of runoff is confined to channels, site erosion can also be reduced. Diversion and collection includes dikes and berms, ditches, channels, diversions; waterways, terraces and benches; and chutes and downpipes.

Diversion and collection systems are most applicable to landfills, surface impoundments, and waste piles. They are typically used in conjunction with grading, revegetation and surface sealing to prevent surface water runon, and to reduce erosion. Preventing run-on has the effect of reducing infiltration of surface water into wastes, thereby reducing leachate generation. Reducing erosion will minimize the likelihood of surface waters directly contacting wastes and subsequently transporting hazardous constituents to soil and ground water.

Revegetation--

Revegetation is typically used following grading and development of diversion and collection systems. Revegetation stabilizes topsoil of covered sites and areas disturbed by earth-moving activities. By binding together soil particles and by reducing surface water flow velocities, revegetation helps to control erosion. Vegetation may increase infiltration by retaining water or may reduce infiltration due to increased evapotranspiration. Vegetation may also treat contaminated soil and ground water through the uptake and removal of hazardous constituents, nutrients, and water from the soil.

Revegetation should include selection of plant species appropriate for site conditions. Temporary erosion control measures such as mulching or spraying surficial soils with binders may be required while vegetation is becoming established. Maintenance will be required to repair erosion rills until vegetation is established. Maintenance may also require periodic mowing to control species development.

Site Management--

Permitted facilities usually have a number of structures designed to reduce the potential for release of hazardous constituents to ground water. These structures include dikes around surface impoundments, sediment traps, diversion and collection channels, cover material and liners at landfills, and concrete aprons and containment dikes at transfer stations and storage facilities and around tanks. Although facility design may incorporate such preventative measures, releases to ground water may occur as a result of:

- insufficient maintenance of facilities;
- inexperience and lack of training for employees; or
- exceeding the design capacity of the facility.

Improved site management may be an appropriate corrective measure for preventing future releases from permitted facilities.

Ground-Water Control/Treatment Technologies

Ground-water control/treatment technologies can generally be classified under four categories. These are:

- impermeable barriers;
- well systems;
- interceptor systems or subsurface drains; and
- *in situ* treatment.

Impermeable barriers, a form of passive ground-water control, can be used to divert ground-water flow away from a waste disposal site or to prevent contaminated ground water from migrating away from the site. Various methods and materials can be used to construct impermeable ground-water barriers such as bentonite slurry, cement or chemical grouts, or sheet piling, as discussed in the following sections. However, before an impermeable barrier is selected to control ground-water flow, it should be recognized that impeded ground-water flow may cause an increase in upgradient hydraulic head, with consequent associated effects on rates of vertical movement of water. The probable effects of a locally heightened water table should be carefully considered before deciding to apply this method of control. Additionally, to meet the 40 CFR Part 264.100(b) corrective action requirements, impermeable barriers must be used in conjunction with pumping and treatment measures.

Well systems encompass the most common techniques used for ground-water pollution control/treatment. They enable the pumping of ground water for subsequent treatment. Ground-water pumping, an active remedial measure, can be specifically designed to manipulate the water table and, thus the subsurface hydraulic gradient in the area of a disposal site through either withdrawal or injection of water, or it can be designed to contain a contaminated ground-water plume. Well systems include well points, deep wells and recharge systems.

Interceptor systems or subsurface drains are horizontal collector systems used to intercept contaminated ground water in shallow aquifers or to lower shallow ground-water tables. The most common example of a subsurface drain is a leachate collection system used to collect leachate below liners of land storage or disposal facilities. The results rendered from the use of subsurface drains are very similar to those of well-point systems. There are two types of interceptor systems used to manage ground-water pollution; these are collector drains and interceptor trenches. Both systems are very similar in terms of design, construction, and results rendered.

In situ treatment enables direct treatment of contaminated ground water by introducing a reactant into the contaminated region to interact with the hazardous constituent plume. The principal variations are permeable treatment beds, chemical injection, and in situ biological treatment (bioreclamation).

The following subsection discusses, in detail, the technologies associated with these four ground-water control/treatment categories. Technology discussions include a generic description of the control/treatment technology and associated system types, and provides guidance on technology applications, data requirements and associated advantages and disadvantages.

Impermeable Barriers--

SLURRY CUT-OFF WALLS--Slurry cut-off walls (or simply, slurry walls) are vertical, low permeable barriers used for capturing, diverting, or containing contamination in ground water. Cut-off walls are gaining widespread application in the area of hazardous waste management. However, as a corrective measure, they do not remove hazardous constituents or eliminate constituent problems, as required by 40 CFR Part 264.100(b). Thus, additional remedial measures must be implemented at a site to meet the required ground-water protection standard.

- *Types of Cut-Off Walls* - The type of cut-off wall is defined by the material used to backfill the trench. There are basically three types of slurry cut-off walls: soil-bentonite, cement-bentonite, and diaphragm.

- Soil-bentonite cut-off walls--Soil-bentonite (SB) walls are composed of soil materials (often trench spoils) mixed with small amounts of bentonite slurry from the trench. In general, SB walls can be expected to have the lowest permeability, the widest range of waste compatibilities, and the least cost (EPA, 1984). However, they also offer the least structural strength and require the largest work area of any of the types of walls. Soil-bentonite walls are usually used where low permeabilities are needed and structural strength is not a problem.

- Cement-bentonite cut-off walls--Cement-bentonite (CB) walls are composed of a slurry of Portland Cement and bentonite which is left to set or harden to form the final wall. CB walls can be constructed in more extreme topographies than SB walls by allowing the wall to harden while continuing the construction of the wall to higher or lower elevations. They also require less work-area in terms of construction. CB walls are stronger than SB walls but usually have at least an order of magnitude higher permeability than SB walls (EPA, 1984).

- Diaphragm Walls--Diaphragm walls are composed of pre-cast or cast-in-place reinforced concrete panels (diaphragms). They are stucturally the strongest of the three tupes of walls as well as the most costly. They usually have about the same permeability as CB walls and because of a similarity of materials about the same compatibility. However, because they are more expensive tha SB walls and CB walls without offering more protection, diaphragm walls are seldom used for ground-water pollution control.

- Applications - Slurry walls have many different applications. There are a number of horizontal and vertical configurations of slurry walls and, at different sites, slurry walls are used in conjunction with many different remedial measures. The effectiveness of the slurry wall is determined, to a large extent, by its configuration and associated remedial measures. There are two types of vertical configurations of slurry walls:

1. Keyed in walls; and
2. Hanging walls.

There are three types of horizontal configurations of slurry walls:

1. Circumferential wall placement;
2. Upgradient wall placement; and
3. Downgradient wall placement.

Four types of remedial measures are often used in conjunction with slurry walls to imporve their effectiveness. These are ground-water pumping, surface and subsurface collection, surface sealing, and grouting, sheet piling of synthetic membrane installation. These measures and the above listed configurations are discussed below.

- Vertical Configurations--Slurry walls may either be keyed into a low permeability layer beneath the aquifer (bedrock) or placed to intercept only the upper portion of the aquifer. A keyed in wall is required if the hazardous constituents are is apt to migrate vertically and horizontally within the aquifer. The connection between the wall and the bedrock is very important to the overall effectiveness of the wall. A suitable key in may be difficult to attain if the bedrock is difficult to excavate or if the bedrock is jointed or contains cracks.

  Hanging slurry walls are not keyed into the bedrock. They are exclusively used to control hazardous constituents which float on top of the ground water (e.g. petroleum products, hydrocarbons). The depth of wall placement will depend on the thickness of the hazardous constituent layer.

- Horizontal Configurations--Different horizontal configurations are used in different slurry wall applications. Circumferential wall placement refers to placing a slurry wall completely around the wastes contained within the site. This configuration is common practice. When used in conjunction with surface water infiltration barriers (caps), circumferential slurry walls can greatly reduce the amount of leachate generated from a waste disposal site. Inward hydraulic gradients are often maintained by the use of extraction wells inside the contained area. A circumferential slurry wall is illustrated in Figure 2.1.

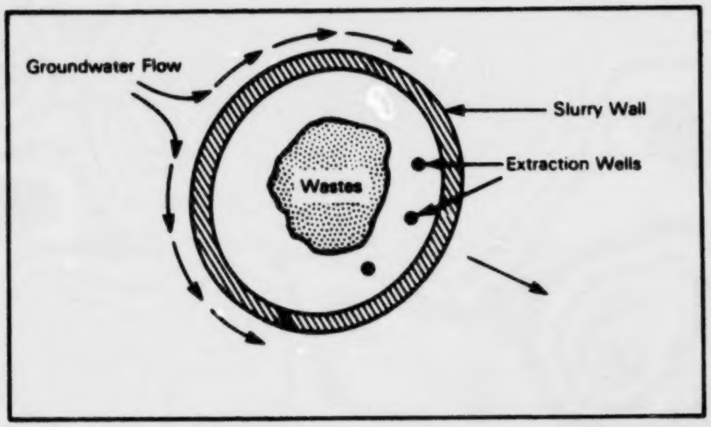


Figure 2.1. Plan of circumferential wall placement.

Source: EPA, 1984.

Upgradient placement refers to the placement of a wall on the upgradient side of the waste site. This configuration is used to divert uncontaminated ground water around the site to prevent clean water from becoming contaminated. A high ground-water gradient is required for this strategy to be effective. That is, unless the ground water can be diverted around the site, and be drained to a lower elevation, it can flow around and return to the same elevation or rise to the surface to overtop the wall (EPA, 1984). The use of a subsurface drainage system may be required to promote drainage around the site. Upgradient wall placement is illustrated in Figure 2.2.

Downgradient wall placement refers to the placement of the wall downgradient of the waste site. This configuration is only practical where there is a relatively small amount of upgradient ground-water flowing through the site. In this application, the slurry wall acts as a barrier to contain contaminated ground water so that it can be recovered for treatment or use. In this case, compatibility of the wall with the hazardous constituent plume is extremely important. Extraction wells will be employed to withdraw the contaminated ground water and to limit the head build-up on the wall. Downgradient wall placement is illustrated in Figure 2.3.

Different combinations of vertical and horizontal wall configurations will be used in different applications. Table 2.1 proides a summary of the effects of different combinations of configurations and indicates where they can be used.

Slurry walls are often used in combination with other technologies to form an effective remedial measure. Ground-water pumping is often required to prevent head build up on a wall and to extract contaminated ground water that is coming in contact with the wall. Surface or subsurface collection is often required to promote drainage around a slurry wall and to improve the effectiveness of the slurry wall. As stated previously, surface sealing (capping) is often used in conjunction with circumferential walls to decrease the generation of hazardous constituents. Grouting is often required to promote the integrity of the bedrock key. Sheet piling and sythetic membrane placement along a wall may increase the structural stability of the wall and decrease its permeability. Reference should be made to EPA 1984 for further information on slurry cut-off walls.

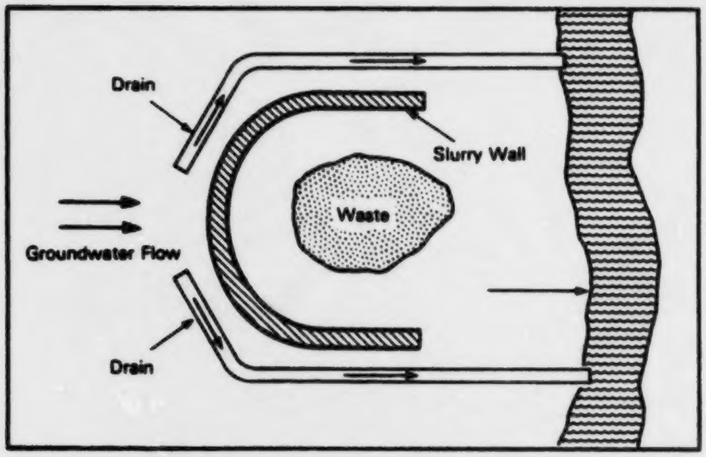


Figure 2.2. Plan of upgradient placement with drain.

Source: EPA, 1984.

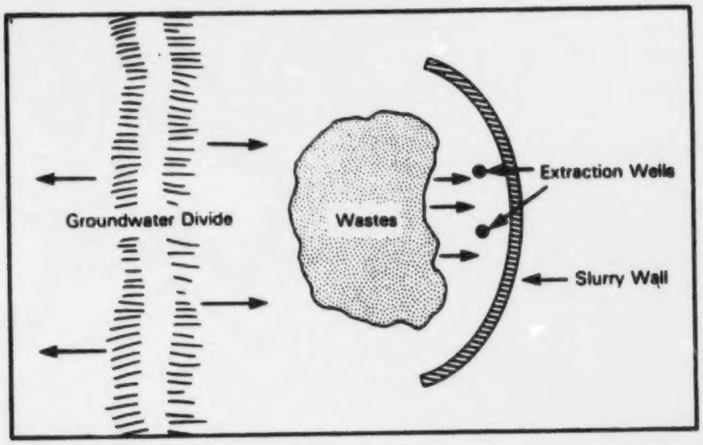


Figure 2.3. Plan of downgradient placement.

Source: EPA, 1984.

TABLE 2.1. SUMMARY OF SLURRY WALL CONFIGURATIONS

Vertical Configuration	Horizontal Configuration		
	Circumferential	Upgradient	Downgradient
Keyed-in	Most common and expensive use Most complete containment Vastly reduced leachate generation	Not common Used to divert ground wate around site in steep gradient situations Can reduce leachate generation Compatibility not critical	Used to capture miscible or sinking contaminants for treatment or use Inflow not restricted, may raise water table Compatibility very important
Hanging	Used for floating contaminants moving in more than one direction (such as on a ground water divide)	Very rare May temporarily lower water table behind it Can stagnat leachate but not halt flow	Used to capture floating contaminants for treatment or use Inflow not restricted, may raise water table Compatibility very important

Source: EPA, 1984

- Data Requirements - In order to design a slurry cut-off wall, a number of site specific characteristics should be known. The design should be preceded by a hydrogeologic investigation of the site. Data obtained should provide information on site soil, ground-water and aquifer characteristics to assist in determining the suitability of the soil for use in slurry or backfill and the expected lifetime and effectiveness of the wall.

Soil characteristics should include:

- texture - granular or cohesive;
- grain size distribution and gradation;
- moisture content;
- permeability; and
- soil pressure.

Ground-water characteristics should include:

- depth to water table;
- direction and rate of flow;
- pH;
- hardness;
- salt concentration;
- presence of other minerals and organics;
- water pressure; and
- hazardous constituent plume characteristics such as chemistry, size and location.

Site soil characteristics assist in determining the suitability of the soil for use in the slurry or the backfill and also in calculating the expected lifetime and effectiveness of the wall. Ground-water characteristics determine construction requirements such as additions and required strength and also contribute to the wall lifetime determination.

Aquifer characteristics should include:

- permeability and thickness of the water bearing strata;
- hydraulic gradient of the aquifer; and
- aquiclude characteristics such as depth, permeability, degree of jointing, hardness and continuity.

Other information which should be provided includes the depth to low-permeability stratum or bedrock to determine the optimal depth of the wall; and the accessibility of suitable soil and bentonite in order that potential cost and implementability can be determined.

Conceivably one of the most important characteristics of the slurry wall that must be investigated before it is designed is its potential compatibility with the hazardous constituents existing at the site. Many types of constituents have been shown to degrade a slurry wall by increasing its permeability. The types of constituents that are most incompatible with slurry mixtures are concentrated organics and highly acidic constituents (Anderson and Jones, 1983). The compatibility of the backfill used for wall construction with the slurry must also be investigated.

- Advantages/Disadvantages - Slurry walls are gaining widespread use in hazardous waste management. To date there is little information as to the performance of slurry walls. However, investigations have indicated there is a potential for structural and compatibility problems (Anderson and Jones, 1983). Slurry walls have a finite life and therefore, are not as effective as other corrective measures. Slurry wall construction is a high technology technique and thus, the cost for construction is relatively high compared to other corrective measures. On the other hand, there is little operation and maintenance required; therefore, low O & M costs. Table 2.2 provides a list of the advantages and disadvantages associated with slurry walls.

TABLE 2.2. ADVANTAGES/DISADVANTAGES OF SLURRY CUT-OFF WALLS

Advantages	Disadvantages
1. Construction methods are simple[a]	1. Cost of shipping bentonite from west[a]
2. Adjacent areas not affected by ground water drawdown[a]	2. Some construction procedures are patented and will require a license[a]
3. Bentonite (mineral) will not deteriorate with age[a]	3. In rocky ground, over-excavation is necessary because of boulders[a]
4. Leachate-resistant bentonites are available[a]	4. Bentonite deteriorates when exposed to concentrated organics and highly acidic wastes
5. Low maintenance requirements[a]	
6. Eliminate risks due to strikes, pump breakdowns, or power failures[b]	
7. Eliminate headers and other above ground obstructions[b]	

[a] Tolman, et al., 1978.

[b] Ryan, 1980.

Source: Compiled by Knox, et al., 1984.

GROUT CURTAINS--Grouting is the process of injecting a liquid, slurry, or emulsion under pressure into the soil. The injected fluid moves away from the point of injection to occupy the available pore spaces. This enables the fluid to set or gel into the rock or soil voids, thereby greatly reducing the permeability of and imparting increased bearing capacity to the grouted mass. When properly carried out, this process can result in a curtain or wall that can be a very effective ground-water barrier.

- Types of Grout - In general, grouts are classified as particulate or chemical. Particulate grouts consist of water plus particulate material which will solidify within the soil matrix. Chemical grouts usually consist of two or more liquids which gel when they come in contact with each other. Particulate grouts are generally comprised of either Portland Cement, bentonite, or a mixture of the two. Their primary use is in sealing voids in materials with rather high permeabilities. They are also often used as "pregrouts" with a second injection of a chemical grout used to seal the fine voids. Chemical grouts are a more recent development than particulate grouts with the exception of silicate grout. Silicate-based grouts are the oldest and most commonly used chemical grouts are presented in Table 2.3. Additional information on grout products and their properties are provided in EPA 1982 and EPA 1983.

- Applications - Although grout curtains are useful under certain site specific conditions, due to their relatively high cost they are generally not the method of choice for ground-water control where a less expensive method, such as slurry wall, is practical. Grouts are, however, the most practical and efficient method for sealing fissures, solution channels, and other voids in rock. They can also be very effective in ensuring a water-tight seal where a slurry wall is keyed into bedrock or some other impermeable layer.

TABLE 2.3. TYPES OF GROUT

	Significant Characteristics
Portland Cement or Particulate Grouts	- Appropriate for higher permeability (larger grained) soils - Least expensive of all grouts when used properly - Most widely used in grouting across the U.S. (90 % of all grouting)
Chemical Grouts	
Sodium Silicate	- Most widely used chemical grout - At concentrations of 10-70% gives viscosity of 1.5 - 50 cP - Resistant to deterioration by freezing or thawing - Can reduce permeabilities in sands from 10^{-2} to 10^{-8} cm/s - Can be used in soils with up to 20% silt and clay at relatively low injection rates - Portland cement can be used to enhance water cutoff
Phenoplasts	- Rarely used due to high cost - Should be used with caution in areas exposed to drinking water supplies - Low viscosity - Can shrink (with impaired integrity) if excess (chemically unbound) water remains after setting unconfined compression strength of 50-200 psi in stabilized soils
Lignosulfonate Derivatives	- Rarely used due to high toxicity - Lignin can cause skin problems and hexavalent chromium is highly toxic; both are contained in these materials - Cannot be used in conjunction with Portland Cement: pH's conflict - Ease of handling - Lose integrity over time in moist soils - Initial soil strengths of 50-200 psi
Aminoplasts e.g., urea-formaldehydes	- Rarely used due to high cost - Will gel with an acid or neutral salt - Gel time control is good

(continued)

TABLE 2.3 (continued)

	Significant Characteristics
Acrylamid Grouts	- Rarely used due to toxicity - Should be used with great caution near to drinking water supplies - Readily soluble in water - Manufacture in USA prohibited available as AV-100 from Japan - Can be used in finer soils than most grouts because low viscosities are possible (1 cP) - Excellent gel time control due to constant viscosity from time of catalysis to set/gel time - Unconfined compressive strengths of 50-200 psi in stabilized soils - Gels are permanent below the water table or in soils approaching 100% humidity - Are vulnerable to freeze-thaw and wet-dry cycles, particularly where dry periods predominate and will fail mechanically - Due to ease of handling (low viscosity), enables more efficient installation and is often cost-competitive with other grouts

Kirk and Othmer, 1979; Sommerer and Kitchens, 1980.

Source: Compiled by EPA, 1983

Theoretically, it is possible to place a grout curtain upgradient or downgradient from or beneath a hazardous waste site. As with slurry walls, the placement of a grout curtain upgradient of a waste site can redirect the flow so that ground water no longer flows through the wastes that are creating hazardous leachate. For a normal range of ground-water chemistries, most grouts could be expected to function well in this capacity. Figure 2.4 indicates the orientation of a grout curtain upgradient for a waste site.

Placement of a grout curtain downgradient from or beneath a hazardous waste site, however, is not as accommodating. Problems could be expected when attempting to grout in the presence of leachate or extreme ground-water chemistry, for example, difficulty or impossibility in controlling the set time and consequently emplacement of a curtain of reliable integrity. Additionally, in order to grout a horizontal curtain or layer beneath a waste site, injection holes most be drilled either directionally from the site perimeter or down through the wastes. The first situation would be very expensive and the second could be very dangerous. In either case it would be very difficult to place an effective barrier and virtually impossible to monitor its effectiveness.

Additionally, as with slurry cut-off walls, grout curtains only provide a means of hazardous constituent control and therefore, require the use of other remedial measures to be in accordance with 40 CFR Part 264.100(b). Other remedial measures may include ground-water pumping (well systems), surface and subsurface collection/drainage systems, surface sealing, slurry or sheet pile cut-off walls or synthetic membranes.

- Data Requirements - Prior to grout injection, a thorough hydrogeologic study of the site must be completed.

Required site soil characteristics include:

- grain size distribution;
- moisture content;
- permeability;

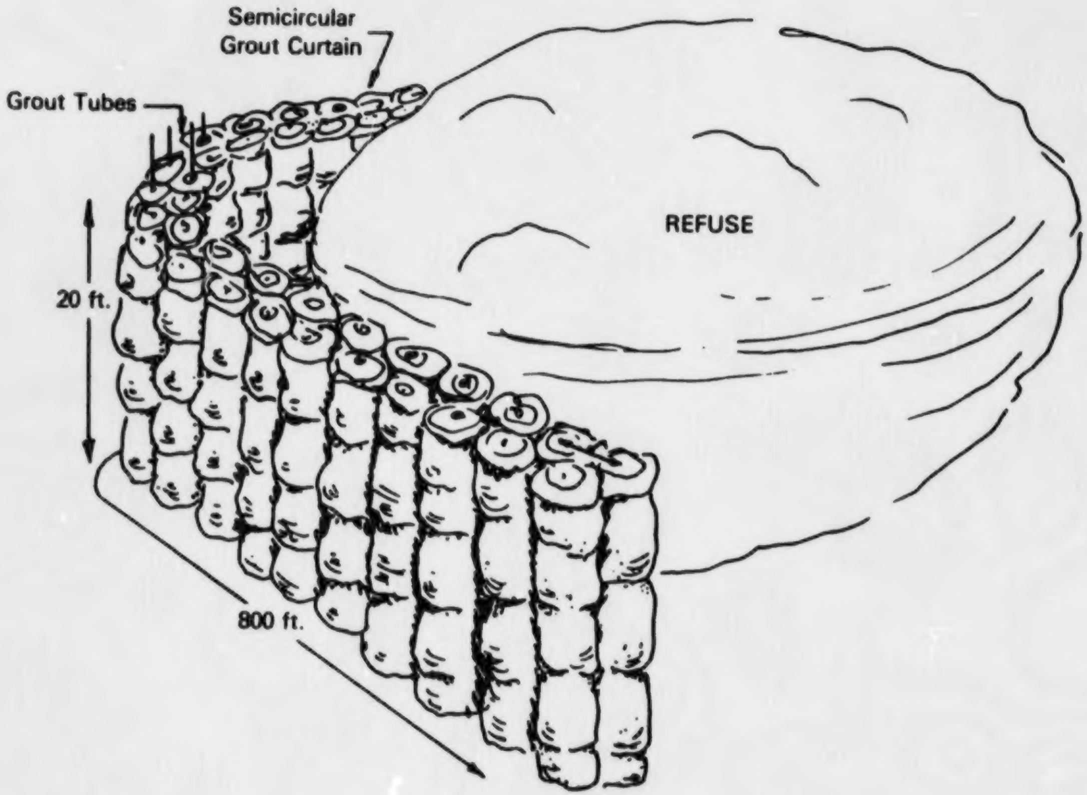


Figure 2.4. Semicircular grout curtain around upgradient end of landfill.

Source: EPA, 1978a.

- porosity; and
- composition (chemistry).

These soil characteristics assist in determining soil groutability, grout pentration, rate of injection and grout material selection. Site soil is not considered suitable for grouting if more than 20 percent of the soil passes through a No. 200 sieve (Sommerer and Kitchens, 1980).

Ground-water characteristics should include:

- depth to water table;
- direction and rate of flow;
- pH;
- concentration of sulfides and calcium; and
- hazardous constituent plume characteristics such as chemistry, size and location.

These ground-water characteristics are indicative of grout material selection and thus, wall construction. Additionally, ground-water flow can adversely affect the integrity of a grout curtain, particularly during construction. Special consideration should be given to rate of flow and chemical composition of the ground water (Sommerer and Kitchens, 1980). After grout material selection, grout characteristics such as strength properties, viscosity and gelation time assist in determining the grout curtain's potential performance as a barrier to ground-water flow.

Other data requirements include: accessibility of grout equipment and materials such that implementability and cost can be determined; and depth to low permeability stratum or bedrock to determine optimal wall depth.

- Advantages and Disadvantages - The technology of grouting, as applied to ground-water pollution control, is very recent. Its potential as a means of stopping or rerouting ground-water flowing in porous rock is fairly high. Grouts can be formulated to set within a few seconds so that even rapidly flowing water can be shut off. Grout can also be used to control ground-water flow in soils, but in most cases, a more cost effective method is available. Although its potential applicability to ground-water control is evident, grouting procedures require specialized techniques and equipment. In addition to these considerations, Table 2.4 provides a list of advantages and disadvantages associated with grout systems.

SHEET PILE CUT-OFF WALLS--As with slurry walls and grout curtains, sheet piling can be used to form a continuous ground-water barrier to control ground-water contamination. However, it also requires additional remedial measures to meet with the 40 CFR Part 264.100(b) regulations. Sheet piling involves driving lengths of interlocking steel into the ground with a pneumatic or steam driven pile driver to form a thin impermeable barrier to flow. Sheet piles can be made of wood, precast concrete or steel. Wood is an ineffective water barrier, however, and concrete is used primarily where great strength is required; therefore, since steel is effective in terms of ground-water cut-off and cost it receives primary emphasis for this application (EPA, 1982).

- Applications - In terms of its application to ground-water pollution control, sheet piling has seen minimal, if any, use. However, similar to slurry walls (particularly) and grout curtains, sheet pile cut-off walls can form barriers that will redirect ground-water flow around or below the depostied wastes. Sheet piling is very applicable to controlling hazardous leachate generation for locations where wastes are deposited in contact with a permanent or seasonal water table.

Sheet piles are typically used in soils that are loosely packed and predominantly sand and gravel. A penetration resistance of 4 to 10 blows/foot for medium to fine - grained sand is recommended. Piling lifetime depends on hazardous constituent characteristics and pile material. For steel piles, pH is of particular importance. Ranges of pH from 5.8 to 7.8 enables a lifetime of up to 40 years (depending on other hazardous constituent characteristics), and pH as low as 2.3 can shorten the lifetime to 7 years or less (EPA, 1983). Additionally, sheet piles should extend to bedrock or other impermeable strata

TABLE 2.4. ADVANTAGES/DISADVANTAGES OF GROUT SYSTEMS

Advantages[a]	Disadvantages
1. When designed on basis of thorough preliminary investigations, grouts can be very successful.	1. Grouting limited to granular types of soils that have a pore size large enough to accept grout fluids under pressure yet small enough to prevent significant pollutant migration before implementation of grout program.[b]
2. Grouts have been used for over 100 years in construction and soil stabilization projects.	2. Grouting in a highly layered soil profile may result in incomplete formation of a grout envelope.[b]
3. Many kinds of grout to suit a wide range of soil types are available.	3. Presence of high water table and rapidly flowing ground water limits groutability through: a. extensive transport of contaminants; b. rapid dilution of grouts.[b]
	4. Some grouting techniques are proprietary.[a]
	5. Procedure requires careful planning and pretesting. Methods of ensuring that all voids in the wall have been effectively grouted are not readily available.[a]

[a] Tolman, et al., 1978.

[b] Huibregtse and Kastman, 1981.

Source: Compiled by Knox, et al., 1984.

to be effective. However, steel piles should not be considered for use in very rocky soils, even if enough force can be exerted to push the piles around or through cobbles and boulders, because the damage to the piles would be likely to render the wall ineffective.

- Data Requirements - After completion of a thorough hydrogeologic investigation, site suitability for sheet pile use and potential pile lifetime and pile placement can be determined.

Required soil characteristics include:

- grain size distribution; and
- compaction.

These characteristics are indicative of the soils' suitability for sheet pile use.

Information on ground-water characteristics should include:

- depth to water table;
- pH; and
- hazardous constituent plume chemistry, size and location.

Pile lifetime and placement can be detemined from these ground-water characteristics. Information should also include the depth to low-permeability stratum or bedrock so that the optimal depth of the sheet pile wall can be calculated.

- Advantages and Disadvantages - Construction of steel sheet piles as a means of ground-water control can potentially be effective and economical in specific cases. In general, however this is probably an over-elaborate technique to achieve a relatively simple result. As the size of a project increases, sheet piling will become uneconomical because of high material and shipping costs. In addition, pile driving requires a relatively uniform, loose boulder-free soil for ease of construction. Other advantages/disadvantages are listed in Table 2.5.

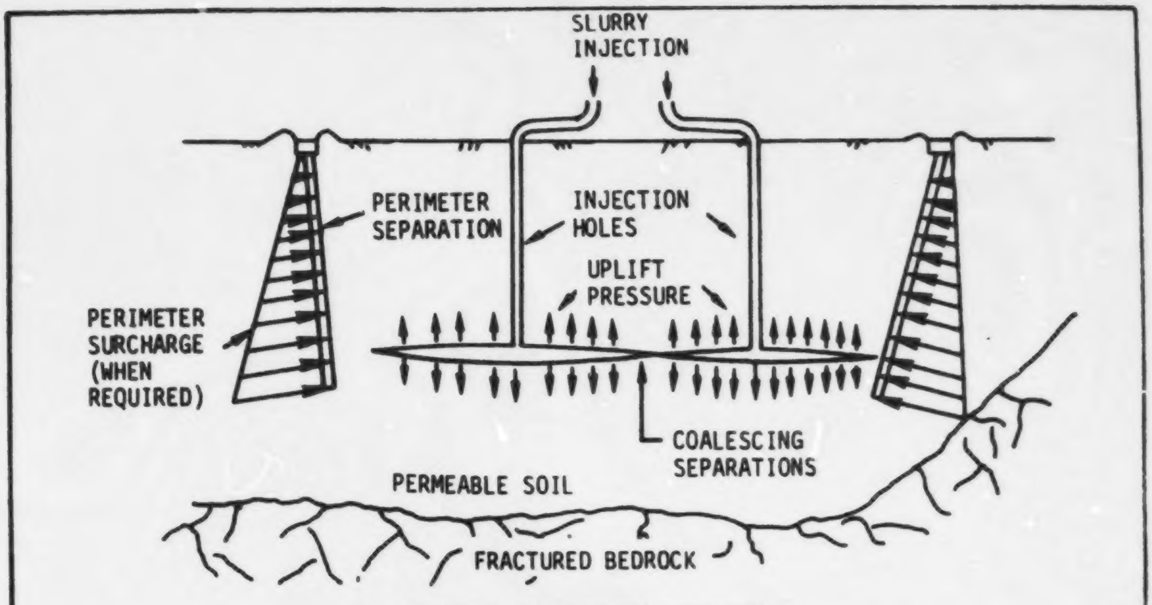
BLOCK DISPLACEMENT METHOD--Block displacement method is a control technology, similar to the other impermeable barrier technologies in that it requires the use of additional remedial measures to meet the 40 CFR Part 264.100(b) regulation, for placing a fixed underground physical barrier around and beneath a fixed mass of earth (called a block) to confine and contain the existing region of hazardous constituents and prevent further spread. The bottom barrier is formed when fractures (or separations) extending from horizontal notches at the base of the injection holes coalesce into a larger separation beneath the mass block of earth. Continued pumping of slurry under pressure produces a large uplift force against the bottom of the block and results in vertical displacement proportional to the volume of slurry pumped. A perimeter barrier around the block is constructed by conventional techniques in conjunction with the bottom barrier either prior to or following bottom barrier construction. The perimeter wall constructed prior to bottom separation can be used to ensure a favorable horizontal stress field for proper formation of the bottom separation. In geologic foramtions not requiring control of horizontal stress, the perimeter may be constructed following initial bottom separation or following the completion of block lift (EPA, 1983).

Although in the developmental stage, the block displacement method can be used to contain contaminated ground water, direct uncontaminated ground-water flow around a (potentially) contaminated area, and lower the water table inside the isolated area. A typical block displacement barrier is shown in Figure 2.5. For further information on the block displacement method refer to EPA 1983.

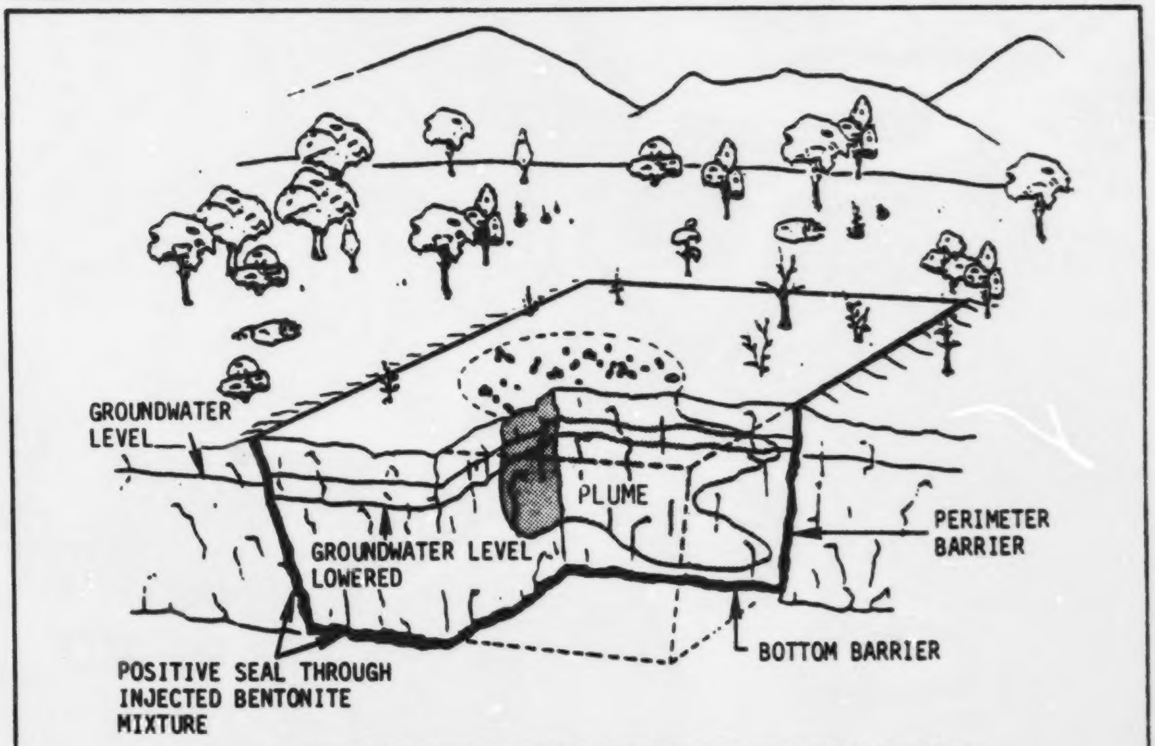
TABLE 2.5. ADVANTAGES/DISADVANTAGES OF STEEL SHEET PILES

Advantages	Disadvantages
1. Construction is not difficult; no excavation is necessary.	1. The steel sheet piling initially is not watertight.
2. Contractors, equipment, and materials are available throughout the United States.	2. Driving piles through ground containing boulders is difficult.
3. Construction can be economical.	3. Certain chemicals may attack the steel.
4. No maintenance required after construction.	
5. Steel can be coated for protection from corrosion to extend its service life.	

Source: Tolman, et al., 1978.



a) CREATING THE BOTTOM SEPARATION



b) CONFIGURATION OF FINAL BOTTOM AND PERIMETER BARRIERS

Figure 2.5 Block displacement method.
Source: EPA, 1983.

o Applications--The block displacement method is of particular value in strata where unweathered bedrock or other impermeable continuum is not sufficiently near the surface for a perimeter barrier alone to act as an isolator. The permeability of the bottom barrier depends both on the filter cake that forms on the separation surfaces and on the permeability of the entire barrier approaches that of the filter cake. Permeabilities of 10^{-8} cm/sec are attainable with proper slurry design.

The effectiveness of the bottom barrier is based on the permeability of the consolidated slurry material and the thickness of the barrier. Effectiveness of the perimeter barrier is dependent on the perimeter construction technique. In general, the perimeter should be designed with an overall effectiveness compatible with the effectiveness of the bottom barrier (EPA, 1983) These barriers should be compatible with in situ soil, ground water and hazardous constituent plume conditions.

- Data Requirements--Upon completion of a thorough hydrogeologic investigation, site soil and ground-water characteristics can be used to determine the suitability of the soil for use in soil bentonite slurry and the expected lifetime and effectiveness of the barrier, and construction requirements such as additives and required strength, respectively.

Required soil characteristics include:

- discontinuities in soil strata in region of expected bottom barrier construction;
- cohesive and consolidation states of individual strata;
- degree and orientation of soil stratification and bedding;
- absolute value and variation of soil permeability in individual strata;
- proximity of weathered bedrocks or solution channels to expected bottom barrier region;
- texture and grain size distribution;

- moisture content; and
- soil pressure.

Ground-water characteristics should include:

- depth of water table;
- direction and rate of flow;
- pH;
- hardness; and
- hazardous constituent plume characteristics such as chemistry, size and location.

Additionally, the accessibility of suitable soil and bentonite should be determined to indicate the potential cost and implementability of the block displacement method.

- Advantages and Disadvantages - Advantages and disadvantages associated with the block displacement method are presented in Table 2.6.

Well Systems--

WELL POINTS--A well point system is used to withdraw ground water in shallow, unconfined aquifers. It consists of a number of closely-spaced, shallow wells which are connected to a main header pipe and ultimately to a centrally located centrifugal pump. Well point systems are only practical for shallow aquifers because of the suction lift limits of the centrifugal pumps. The primary design consideration for well point systems is the drawdown of the system. The system should be designed so that the spacing of the wells and the drawdown potential of the system are sufficient ot intercept the plume of hazardous constituents. Spacing of the well points and drawdown potential depend on site-specific conditions; particularly, the hydraulic conductivity of the aquifer. A typical well point system is shown in Figure 2.6.

TABLE 2.6. ADVANTAGES/DISADVANTAGES OF THE BLOCK DISPLACEMENT METHOD

Advantages	Disadvantages
1. Valuable when impermeable stratum not sufficiently near surface.	1. Bentonite deteriorates when exposed to concentrated organics and highly acidic waste.
2. Bentonite (mineral) will not deteriorate with age.	
3. Leachate - resistant bentonites are available.	

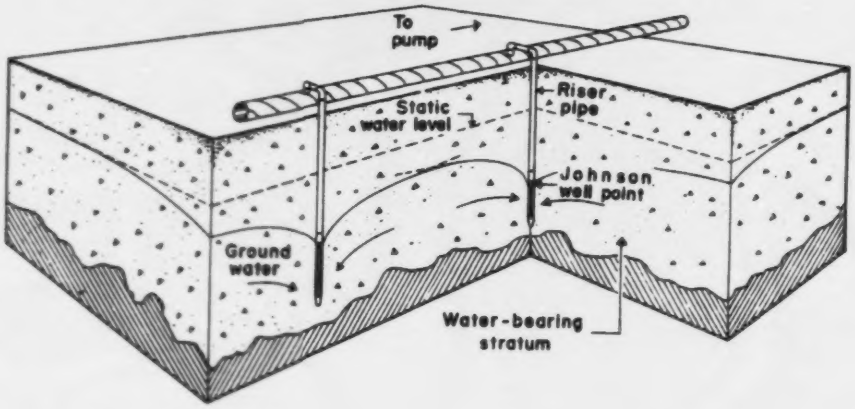


Figure 2.6. Schematic of a well point dewatering system.

Source: Johnson Division, 1975.

DEEP WELL SYSTEMS--Deep well systems can be used to withdraw water from aquifers located at depths of up to several hundred meters. The construction of these systems is similar to that of monitoring wells. The wells are built to house a submersible pump and, therefore, are capable of extracting water from great depths. As with well points, deep well systems must be designed so that the drawdown and well spacing are sufficient to intercept the plume of hazardous constituents.

RECHARGE SYSTEMS--Recharge systems that employ well systems are called pressure ridge systems. These systems can be constructed similarly to either well points or deep well systems. They function as the inverse of these systems. Their purpose is to inject water into a ground-water system to form an upconing of the water table which acts as a barrier to ground-water flow. They can also be used in ground-water circulation systems to assist in isolation and extraction of hazardous constituents in ground water. This concept is discussed in subsequent paragraphs.

Another type of recharge system is a seepage or recharge basin. This system allows water to seep into the ground-water table by gravity flow. These systems are often used in conjunction with downgradient pumping wells to flush hazardous constituents from a specific area. They require continual operation and maintenance to keep the porosities of the basin large.

- Applications - Well systems can be used in a number of applications to control and treat ground-water pollution. In one general category of applications, well systems can be used to manage a plume by containment and/or entraction. In another category they can be used to adjust the water table to prevent ground-water pollution. The specific applications under each category are discussed below.

  - Plume Management--The applications in this category include the following:

    - flushing of the ground water by using a series of extraction and injection wells or seepage basins. The ground water is pumped, treated and used to recharge the aquifer; and

- pumping of the plume without the use of recharged.

Extraction/Recharge Systems--The first application employs both ground-water injection and withdrawal systems. The system, as illustrated in Figure 2.7, is often referred to as a hydrodynamic isolation system. In this application, wells are used to isolate and or extract hazardous constituent plumes. The premise behind this concept lies in the creation of a closed system within which a zone of ground water is isolated and recirculated from recharge wells to pumping wells. As a result, the contaminated zone is flushed and the water extracted. If the pumped water is used for recharge, the system should be incorporated into a scheme where the captured ground water is treated before it is returned into the ground. Further, information on this application can be found in Ozbilgin and Powers, 1984.

A less costly alternative to using injection wells for a source recharge would be to use seepage basins. However, seepage basins require a high degree of maintenance to ensure that porosity is not reduced. Therefore, the use of seepage basins would not be practical where several basins are required.

Pumping Without Recharge--Hazardous constituent plumes can also be extracted by employing pumping well systems alone. The principle of withdrawal systems is illustrated in Figure 2.8. The design of this system is considerably less complicated than the previously mentioned system because recharge is not involved. However, larger volumes of water may have to be pumped. Furthermore, the advantage of ground-water replenishment is not gained. Consequently, undesirable environmental impacts may occur if pumping takes place in aquifers that are in use. This issue must be considered in the selection of a suitable pumping strategy.

- Water Table Adjustment--Well systems can be used to adjust the level of the water table to prevent future ground-water pollution. The applications in this category include the following:

  - lowering of the water table to prevent direct contact with the plume; and

  - upconing of the water table to act as a barrier to plume movement.

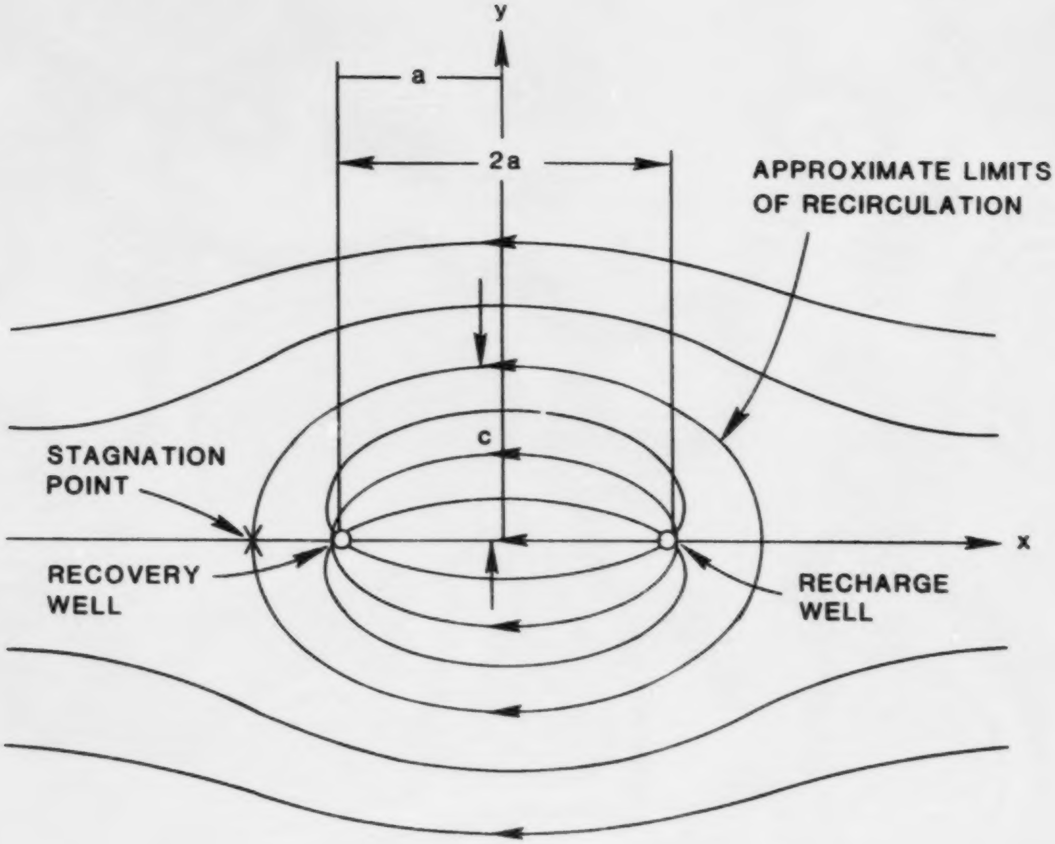


Figure 2.7. Theoretical representation of hydrodynamic isolation system.

Source: Ozbilgin and Powers, 1984.

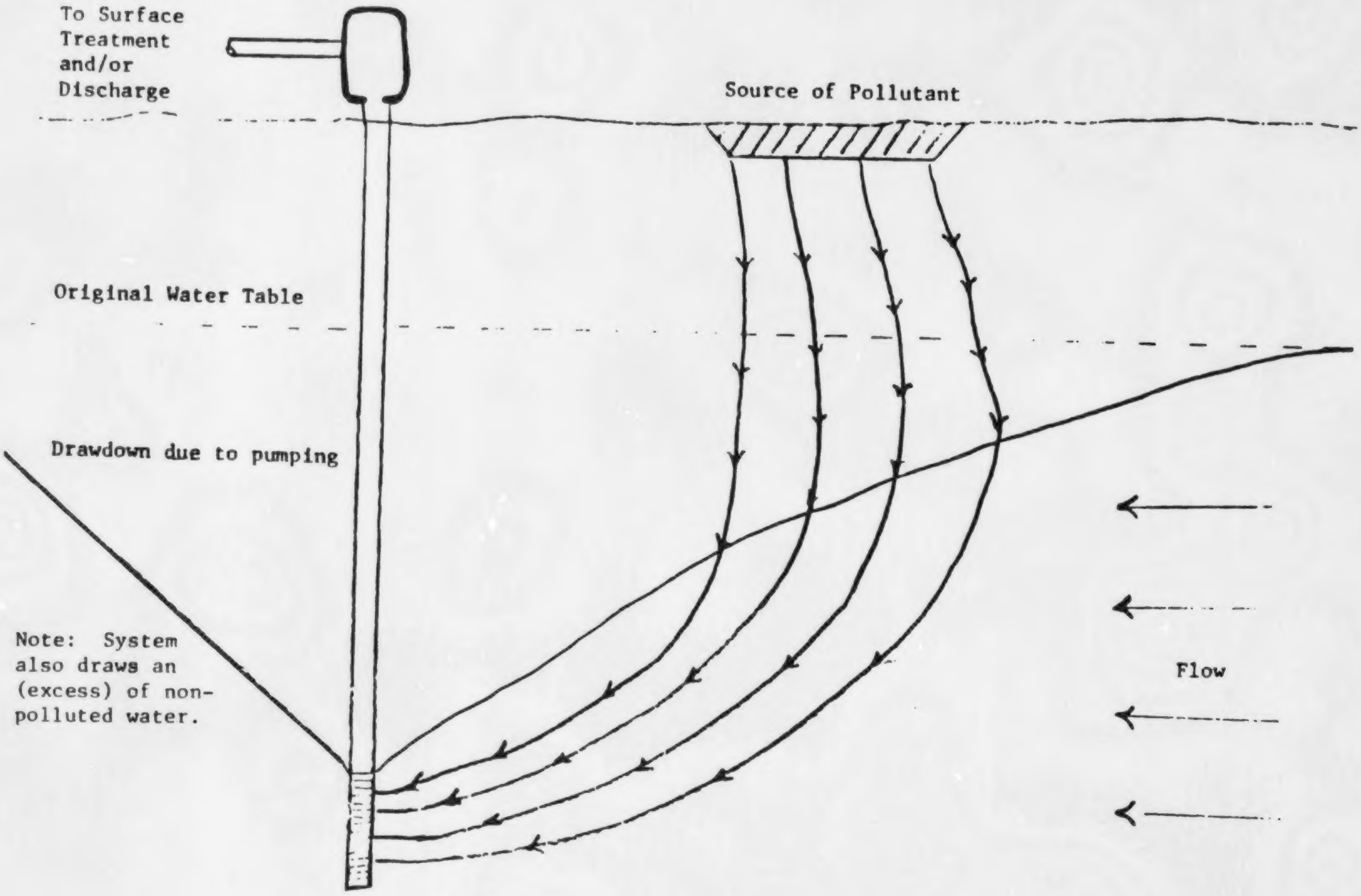

To Surface Treatment and/or Discharge
Source of Pollutant
Original Water Table
Drawdown due to pumping
Note: System also draws an (excess) of non-polluted water.
Flow

Figure 2.8. Principle of withdrawal wells.

Source: Knox et al., 1984.

Water/Table Lowering--This application involves pumping of the ground water to prevent contamination of, or hazardous constituent migration in, the underlying aquifer. By lowering the water table below the hazardous constituent plume, direct contact with the plume, is avoided. Lowering of the water table may be accomplished by locating pumping wells upgradient, downgradient or in both areas.

Raising of Water Table--In this application, water is pumped into the ground water to form an upconing of the water table. As a result, the hazardous constituent plume can be diverted or isolated. This principle is illustrated in Figure 2.9.

In addition to their ability to adjust the water table and contain a plume, well systems (i.e., ground water pumping) can be utilized in conjunction with the other ground-water controls, such as impermeable barriers or subsurface drainage systems, to maximize their efficiency. Although well systems, i.e. pumping, can be expensive compared to other control/treatment technologies, it might be the most practical alternative under certain circumstances, such as when (Doering and Benz, 1972):

- combinations of fine and textured soils or upward hydraulic gradients make subsurface drainage difficult; and
- ground-water conditions are stagnant e.g. hydraulic gradient is nearly zero.

- Data Requirements - The design of any of the well systems must be preceded by a hydrogeologic investigation of the waste disposal site. Data should be provided on soil, ground water, and aquifer characteristics.

Soil characteristics should include:

- grain size distribution; and
- texture.

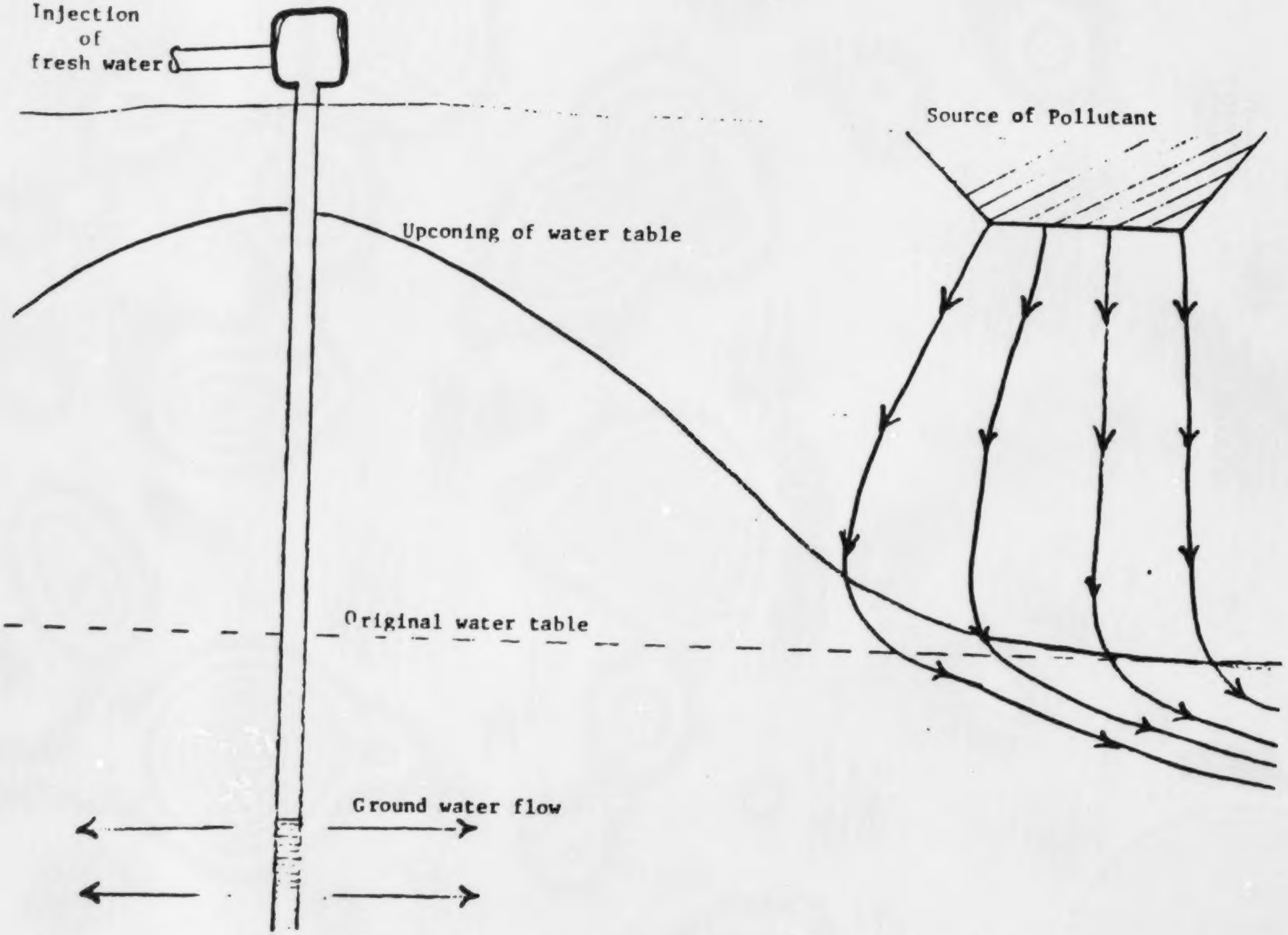


Figure 2.9. Principles of pressure ridge system.

Source: Knox et al., 1984.

These characteristics determine whether site soil is suitable to pumping.

Ground-water characteristics should include:

- depth to water table;
- potentiometric surfaces-hydraulic gradient; and
- recharge quantity.

Ground-water characteristics assist in determining the effectivenss of pumping. The effect of long-term pumping on local ground-water levels should be considered (Sommerer and Kitchens, 1980).

Aquifer characteristics should include:

- permeability and thickness of water bearing strata;
- identification of ground-water flow systems;
- transmissivity;
- storativity;
- effective porosity;
- specific yield;
- hydraulic gradient;
- depth;
- identification of recharge and discharge area;
- type - confined or unconfined;
- condition - homogeneous, leaky, isotropic; and
- extent - limited by barriers or surface water.

Aquifer characteristics, along with ground-water characteristics, determine the effectiveness of pumping. Recharge of the aquifer may be necessary in some cases to maintain water levels or to conform to state law. Therefore, state regulations concerning the maintenance of existing water table levels should be known. Data on the depth to impermeable strata should also be provided to assist in determining the effectiveness of pumping. Additionally, the hydrogeologic study should indicate plume dimensions (width, length, depth and general shape), the hydraulic gradient across the plume, and plume chemistry (Lundy and Mahan, 1982). The above information, along with the concepts of well hydraulics, can be used to establish the well number and spacing, pumping or injection rate, and the necessary drawdown potential of the system. Additional information on well systems, including empirical formulas to calculate the important well system design parameters, is provided in EPA 1982 and Knox, et al. 1984.

- Advantages and Disadvantages - The use of well systems is presently, and will probably continue to be, the most utilized type of corrective measure for release of hazardous constituents to ground water. Well systems are presently the most proven and the most assured means of controlling subsurface flows of hazardous constituents. Well systems are also understood somewhat more than other technologies used for corrective measures. However, due to the extent of operation and maintenance of the system, the amounts of water that may have to be pumped and the large scale construction that may be involved, the cost of a well system by be considerably greater than other technologies. Furthermore, implementation of this technology may require extensive mathematical modeling of the ground-water movement which may not be required in other measures. These and other advantages and disadvantages are summarized in Table 2.7.

Subsurface Drains (Interceptor Systems)--

COLLECTOR DRAINS--Collector drains are commonly used below or near land disposal facilities to intercept hazardous constituents leaking through the liner. They are relatively simple in design and consist of horizontal perforated pipes placed in the ground in a grid configuration. These pipes are connected to a main collector pipe which is connected to a sump. Ground water is conveyed by collector pipes to he sump where it is pumped out for

TABLE 2.7. ADVANTAGES/DISADVANTAGES OF WELL SYSTEMS

Advantages	Disadvantages
1. Efficient and effective means of assuring ground water pollution control.	1. Operation and maintenance costs are high.
2. Can be installed readily.	2. Require continued monitoring after installation.
3. Previously installed monitoring wells can sometimes be employed as part of well system.	3. Withdrawal systems necessarily remove clean (excess) water along with polluted water.
4. Can sometimes include recharge of aquifer as part of the strategy.	4. Some systems may require the use of sophisticated mathematical models to evaluate their effectiveness.
5. High design flexibility.	5. Withdrawal systems will usually require surface treatment prior to discharge.
6. Construction costs can be lower than artificial barriers.	6. Application to fine soils is limited.

Source: Knox, et al., 1984.

subsequent treatment. Collector drains are installed perpendicular to ground-water flow. A typical collector drain system is shown in Figure 2.10. Construction of a collector drain system involves excavating trenches, installing pipes, and backfilling with coarse gravel or sand to prevent particles from clogging the system.

INTERCEPTOR TRENCHES--Interceptor trenches function similarly to collector drains. They are constructed perpendicular to ground-water flow to intercept hazardous constituents. Interceptor trenches can be either active or passive systems. Active systems are either pumped by vertical removal wells or drained by perforated, horizontal collector pipes. Active systems are usually backfilled with coarse sand or gravel for wall stability. Passive systems are open trenches used exclusively for collecting floating pollutants such as petroleum products and hydrocarbons. Skimming pumps are installed for the removal of hazardous constituents only. In trench systems, both pumping and skimming operations must be continuous to prevent the collected hazardoous constituents from seeping into the trench walls. It is recommended that trench walls be lined with an impermeable material to prevent such a phenomenon from occurring. In any case, it is good practice to keep the water level down to the bottom of the trench.

- Applications - Subsurface drains, a control/treatment strategy, has two basic applications in the abatement of ground-water pollution; it either functions as relief drains or interceptor drains. Relief drains are generally installed in areas where the hydraulic gradient is relatively flat (i.e. almost zero). They are often used to lower the water table beneath a site, or to prevent hazardous constituents from migrating to deeper, underlying aquifers. In this application, the drains are installed upgradient or downgradient of the site or around the perimeter of the site so that their areas of influence overlap. (Kufs et al., 1983).

Interceptor drains are used for collection and removal of hazardous constituents in ground water. They are installed downgradient of a pollutant source in order to intercept the migrating plume. Figure 2.11 illustrates the effect of subsurface drains on a ground-water table that will be exhibited in both the relief drain and interceptor drain applications.

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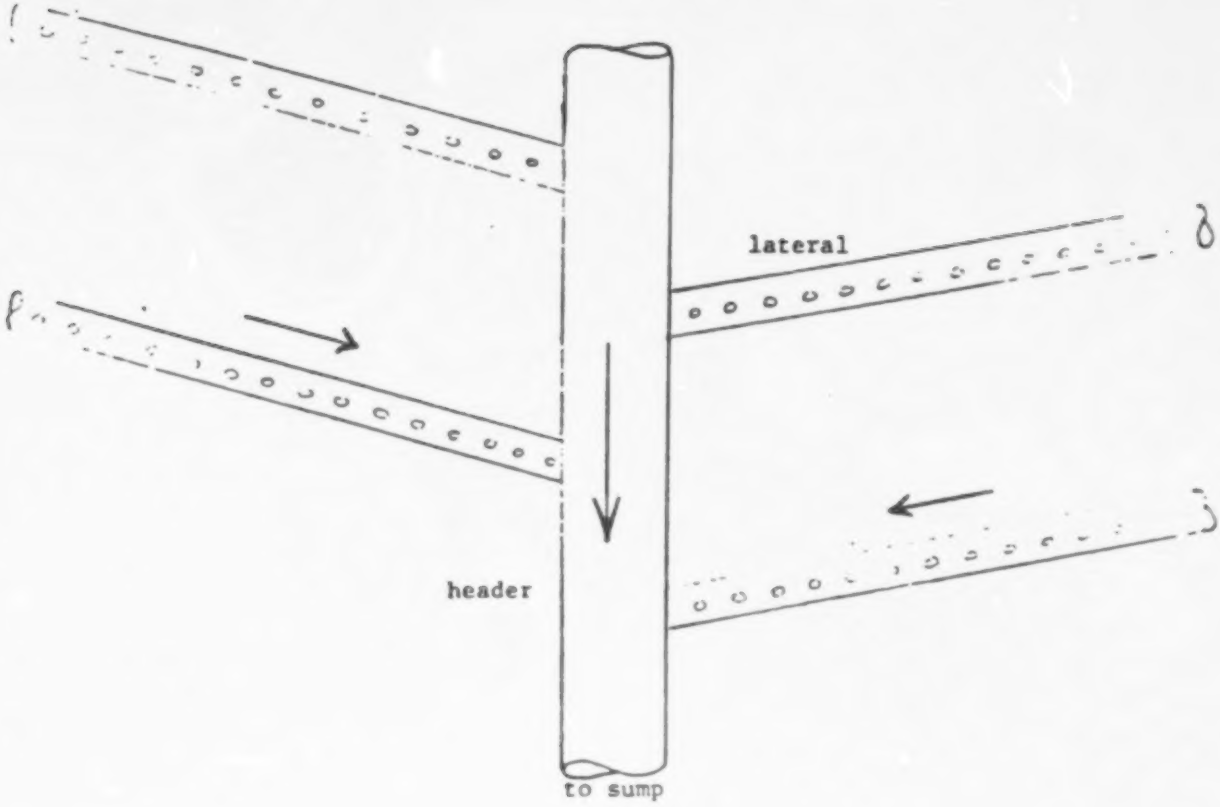
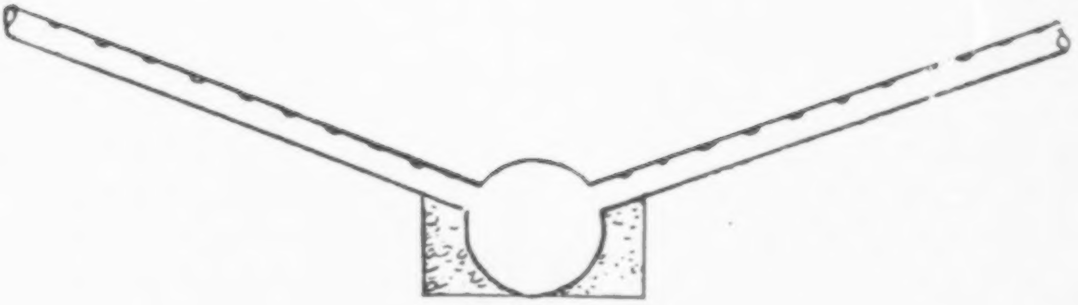


Plan



Profile

Figure 2.10. Collector drain system.

Source: Knox et al., 1984.

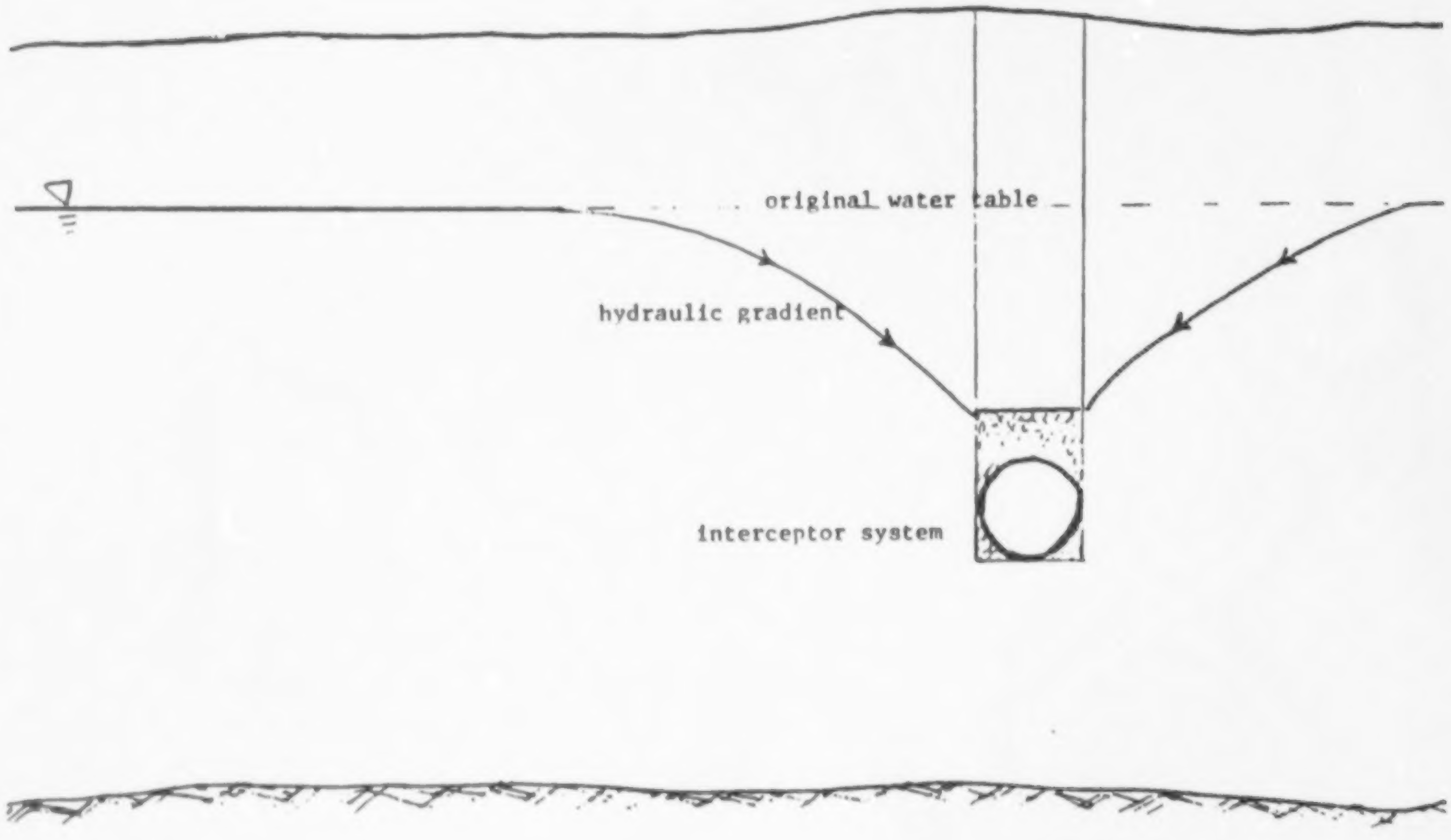


Figure 2.11. Hydraulic gradient toward interceptor system.

Source: Knox et al., 1984.

In a preventative measure subsurface drains are installed beneath and/or around disposal facilities to collect hazardous constituents. The design of the drains in this application are similar to the interceptor drain design. The only difference between the two systems is that the interceptor drains are installed as an abatement measure after pollution has been released. Therefore, the size and location of the drains are designed to accomodate the size and location of the hazardous constituent plume. Furthermore, subsurface drains which collect hazardous constituents are usually installed in unsaturated media so that only hazardous constituents (leachate) is collected. However, the theory behind these two approaches is the same.

- Data Requirements - The data required to design a subsurface drainage system is very similar to that required to design well systems. Essentially, the design must be preceded by a hydrogeologic investigation of the area. This investigation must generate data for the extent and location of contamination and the dimensions of the area that is contaminated. Furthermore, the investigation must render values for the hydrogeologic characteristics of the aquifer. This information should include the following:

  - permeability and thickness of water bearing strate;
  - storativity (degree of confinement);
  - effective porosity of the aquifer;
  - regional hydraulic gradient;
  - identfication of recharge and discharge areas; and
  - identification of aquifer boundaries, vertical leakage and confining layers.

This information is essential to the determination of drain spacing, pipe size, pumping rate at the sump and the drawdown potential of the system. Formulas used to determine these parameters using the above listed data can be found in EPA, 1982 and Knox, et. al., 1984.

- Advantages/Disadvantages - Subsurface drains are a fairly common and proven technology used for corrective and preventative measures for hazardous constituent releases. They are useful only to intercept shallow releases. Subsurface drains are inexpensive relative to other ground-water control/treatment technologies. Furthermore, a plan employing subsurface drains would be relatively easy to implement due to the ease of installation of the non-complex system design. Other advantages and disadvantages of the system are identified in Table 2.8.

In Situ Treatment--

PERMEABLE TREATMENT BEDS--Permeable treatment beds use trenches filled with a reactive permeable medium to act as an underground reactor. Contaminated ground water or leachate entering the bed reacts to produce a nonhazardous soluble product or a solid precipitation.

- Applications - Although in the more or less conceptual stage of development, permeable treatment beds have the potential to physically and chemically treat contaminated ground water in-place. Permeable treatment beds are generally applicable for pollution control/treatment in relatively shallow aquifers since a trench must be constructed down to the level of the bedrock or an impermeable strata. These beds are often only effective for a short time because they lose their reactive capacity or they become plugged with solids. Over-design of the system or replacement of the permeable medium can lengthen the time period over which permeable treatment is effective

  Relatively few materials can be feasibly employed in permeable beds to treat contaminated ground water. These materials include (EPA, 1983):

  - Limestone or Crushed Shell -- Limestone neutralizes acidic ground water and may remove heavy metals such as Cd, Fe, and Cr. Dolomitic limestone ($MgCO_3$) is less effective at removing heavy metals than calcium carbonate limestone. The particle size of the limestone should match a mix of gravel size and sand size. The larger sizes minimize settling of the bed and channeling as the limestone dissolves. The small sizes maximize contact. Extrapolated bench-scale data indicate that the contact time needed to change 1 pH unit is 8 to 15 days.

TABLE 2.8. ADVANTAGES/DISADVANTAGES OF SUBSURFACE DRAINS

Advantages	Disadvantages
1. Operation costs are relatively cheap since flow to underdrains is by gravity.	1. Not well suited to poorly permeable soils.
2. Provides a means of collecting leachate without the use of impervious liners	2. In most instances it will not be feasible to situate underdrains beneath an existing site.
3. Considerable flexibility is available for design of underdrains; spacing can be altered to some extent by adjusting depth or modifying envelope material.	3. System requires continuous and careful monitoring to assure adequate leachate collection.
4. Systems fairly reliable, providing there is continuous monitoring.	4. Open systems may require safety precautions to prevent fires or explosions.
5. Construction methods are simple and inexpensive.	5. Operation and maintenance costs are high.
6. Large wetted perimeter allows for high rates of flow.	6. Not useful for deep disposal sites.
7. Produces much less fluid for handling them well point systems.	

Source: Knox, et al., 1984.

- Activated Carbon -- Activated carbon removes non-polar organic contaminants such as CCl_4, PCBs, and benzene by adsorption. Activated carbon must be wetted and sieved prior to installation to ensure effective surface solution contact.
- Glauconitic Green Sand -- This sand, actually a clay, is found predominantly on the coastal plain of the Mid Atlantic states and has a good capacity for adsorbing heavy metals. Bench-scale studies indicate removal efficiencies of greater than 90 percent for As, Cu, Hg, and Ni, and 60-89 percent for Al, Cd, Ca, Cr, Co, Fe, Mg, Mn and Zn, for detention times on the order of several days.
- Zeolites and Synthetic Ion Exchange Resins -- These materials are also effective in removing solubilized heavy metals. Disadvantages such as short lifetime, high costs, and regeneration difficulties make these materials economically unattractive for use in impermeable treatment beds.

With permeable treatment beds, plugging of the bed may divert contaminated ground water and channeling through the bed may occur. Both problems permit the passage of untreated ground water. Additionally, changing the hydraulic loads and/or hazardous constituent levels may render the detention inadequate to achieve the design removal level. Figure 2.12 illustrates the relative location of a permeable treatment bed to enable ground-water treatment.

- Data Requirements - Prior to installation of a permeable treatment bed hydrogeologic investigations should provide data on hazardous constituent plume characteristics such as:

  - depth to bedrock;
  - plume cross-section;
  - hazardous constituent (i.e., leachate) or ground-water velocity; and
  - hydraulic gradient.

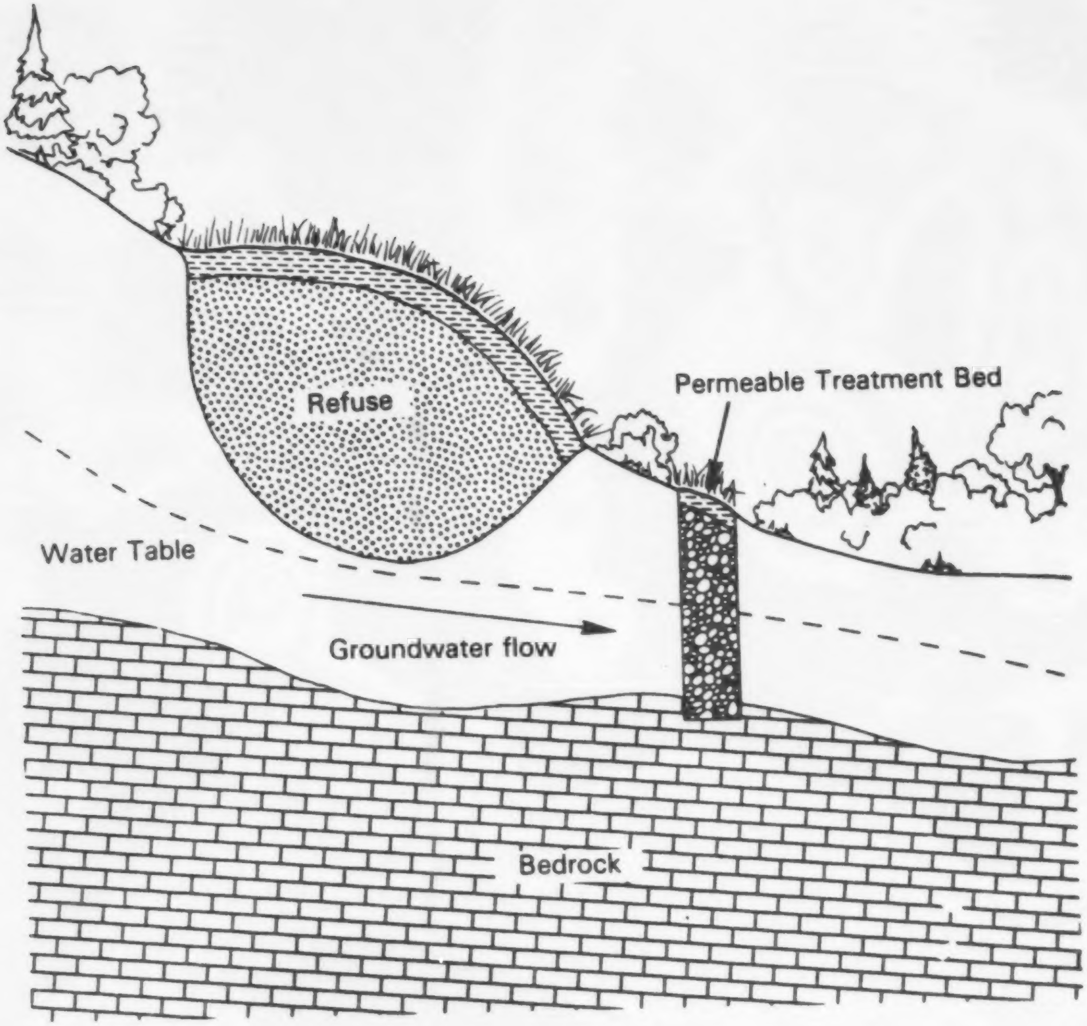


Figure 2.12. Relative location of a permeable treatment bed.

Source: EPA, 1982.

The above plume characteristics as well as soil permeability are required in order to determine the appropriate treatment bed design. Data should also provide information on hazardous constituent composition and reaction rate in order that a reaction medium can be selected and a sufficient contact time be determined.

- Advantages and Disadvantages - Advantages and disadvantages associated with the use of limestone beds, activated carbon beds, and glauconitic green sand beds are summarized in Tables 2.9, 2.10, and 2.11. Zeolite and synthetic ion exchange resins, although very effective in the removal of heavy metal constituents, could be used for removing hazardous constituents in ground water but they are economically and practically infeasible for permeable treatment beds because of problems such as short life, high cost, and re-activation difficulties. Therefore, these materials are not recommended for use except where engineering and economic evaluations prove their desirability in specific cases.

CHEMICAL INJECTION--Chemical injection entails injecting chemicals into the ground beneath the waste to neutralize, precipitate or destroy the leachate constituents of concern (EPA, 1983).

- Applications - Chemical injection, also in the conceptual stage, has seen use in the treatment of hazardous constituent plumes containing cyanide by sodium hypochlorite (EPA, 1983). The use of chemical injection requires that the areal spread and depth of the hazardous constituent plume be well characterized so that injection wells can be placed properly to intercept all of the contaminated ground water. The use of this technique can, however, displace hazardous constituents to adjacent areas due to the added volume of chemical solution. Also, hazardous compounds can be produced by the reaction of injected chemical solution with hazardous constituents other than the treatment target. Refer to Knox, et al., 1984 for a detailed description of specific chemical injection techniques. Figure 2.13 illustrates the cross section of a landfill being treated by chemical injection.

TABLE 2.9. ADVANTAGES/DISADVANTAGES OF CRUSHED LIMESTONE TREATMENT BED

Advantages	Disadvantages
1. Can be used to neutralize a slightly acidic ground water stream.	1. Cementation or solidification of the limestone bed may occur, leading to plugging of the flow.
2. Applicable for the removal of certain heavy metals contained in ground water.	2. Not effective for the removal of organic contaminants.
3. Good potential for successful control for chromate anion present in ground water flow.	3. Solution-channelling through bed may occur.
4. Very cost effective to install since limestone is inexpensive and readily available.	

Source: EPA, 1982.

TABLE 2.10. ADVANTAGES/DISADVANTAGES OF ACTIVATED CARBON TREATMENT BED

Advantages	Disadvantages
1. Very effective in the removal of nonpolar organic compounds from the ground water flow.	1. Plugging of the bed may occur.
2. Readily available and easy to handle and intall.	2. Not very effective for the removal of polar organic compounds.
	3. Presence of other chemicals in the ground water may decrease the effectiveness of bed absorption.
	4. Desorption of the hazardous absorbed materials to the clean water flow may occur, resulting in recontamination.
	5. Removal and disposal of spent activated carbon is difficult and hazardous.
	6. Cost of the material is very high.
	7. Competitive absorption with large organic molecules may decrease the removal effectiveness of the bed.
	8. Life of the bed may be very short in the presence of complex organic compounds such as humic compounds.

Source: EPA, 1982.

TABLE 2.11. ADVANTAGES/DISADVANTAGES OF GLAUCONITIC TREATMENT BED

Advantages	Disadvantages
1. Apparent high effectiveness in the removal of many heavy metals.	1. Saturation characteristics unknown.
2. Good residence time characteristics for efficient treatment; relatively little material required for bed.	2. Area of application probably limited by transportation costs to Mid-Atlantic region.
3. Abundant in New Jersey, Delaware, and Maryland.	3. May require land purchase since it does not seem to be commercially mined.
4. Good metal retention characteristics.	4. Reduction in permeability and plugging of bed may occur after a time.
5. Good permeability.	5. May reduce pH.
	6. Removal efficiencies of metals at high concentrations unknown.

Source: EPA, 1982.

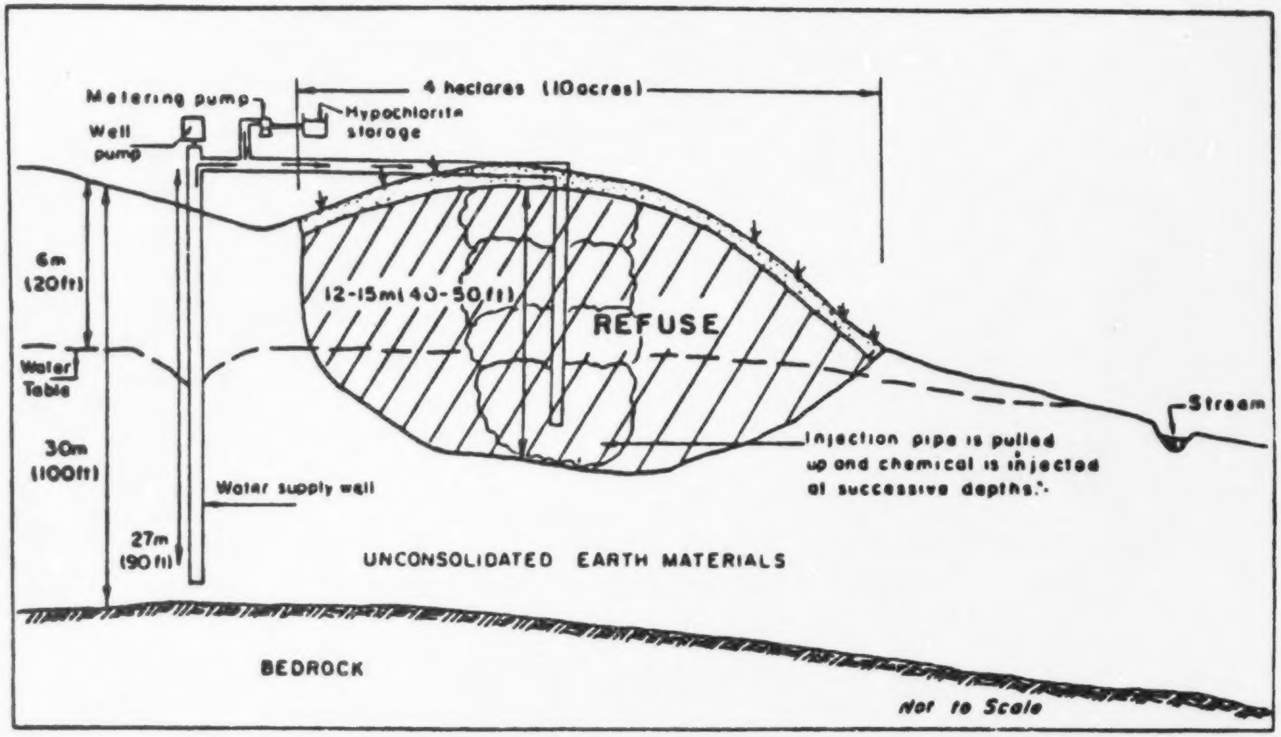


Figure 2.13. Cross section of landfill treated by chemical injection.

Source: EPA, 1983.

- Data Requirements - A site hydrogeologic investigation should be conducted prior to chemical injection to provide data on the areal spread and depth of the plume so that injection wells can be placed properly to intercept all of the contaminated ground water.

- Advantages and Disadvantages - In situ chemical treatment is viable only under particular hydrogeological and geochemical conditions. Other aquifer restoration measures, such as withdrawal and treatment may be more appropriate (Knox et al., 1984).

BIORECLAMATION--Bioreclamation is based on the concept of utilizing microbial organisms combined with aeration and addition of nutrients to accelerate the biodegradation rate of the ground-water contaminants (if contaminants are biodegradable).

- Applications - Bioreclamation has been previously demonstrated to be an effective method of controlling ground-water contamination from underground hydrocarbon spills. The method may also be applied to a clean-up operation of ground-water contaminated by organic hazardous constituents from landfills. The technique can be effectively used to clean-up underground hydrocarbon plumes that contaminate the ground water. However, certain organic substances, such as chlorinated solvents, cannot be very effectively treated.

Application of the bioreclamation method to treat contaminated ground water from waste disposal sites may require slight modifications to the currently employed method. Ground water contaminated with materials that leached from a disposal site may contain a great variety of hazardous substances besides hydrocarbon compounds. Therefore, when the bioreclamation technique that was originally developed for the "in-situ" clean-up of ground water contaminated with hydrocarbons is used, it is necessary to adjust certain factors of the process to accommodate the removal of hazardous constituents that may comprise a wide range of toxic materials (EPA, 1982).

It is recommended that the contaminated ground water be studied to determine the chemical constituents to be removed. Once the hazardous constituents are identified, appropriate bacteria can be chosen to accomplish the desired degradation process.

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The general method of treating contaminated ground water with the biorelamation method is illustrated in Figure 2.14. First, wells are placed at strategic locations with respect to the hazardous constituent plume. Then the chosen microorganisms are injected into the ground water along with oxygen and nutrients. Prior to the injection, the bacteria should be acclimated to the hazardous constituents they are intended to treat. To promote microbial action, a proper balance of oxygen and nutrients is maintained by continuous pumping, makeup, and reinjection into the ground water (EPA, 1982).

Proper aeration can be obtained by purging oxygen into wells by the use of diffusers attached to paint-sprayer-type compressors that can deliver oxygen at a constant volumetric flow rate. The compressors are equipped with pressure gages and relief valves to aid in determining that each diffuser is operating properly (Raymond et al., 1976).

Refer to Knox et al., 1984 for a detailed discussion of the bioreclamation method.

- Data Requirements - In addition to a thorough hydrogeologic investigation, the following information should be identified (EPA, 1982):
    - chemical constituents of the contaminated ground water;
    - type of bacteria most appropriate for the degradation of the hazardous constituents;
    - size of the contaminated ground-water plume;
    - geological data on the site proposed for treatment, including type of subsurface material and permeability; and
    - volumetric flow rate of the ground-water flow and the level of contamination.

- Advantages and Disadvantages - The advantages and disadvantages of the bioreclamation method are summarized in Table 2.12.

A summary of the ground-water control and treatment technologies previously discussed is presented in Table 2.13. Following this, a Permit Writers' Checklist is provided indicating important points to consider when reviewing a permit application.

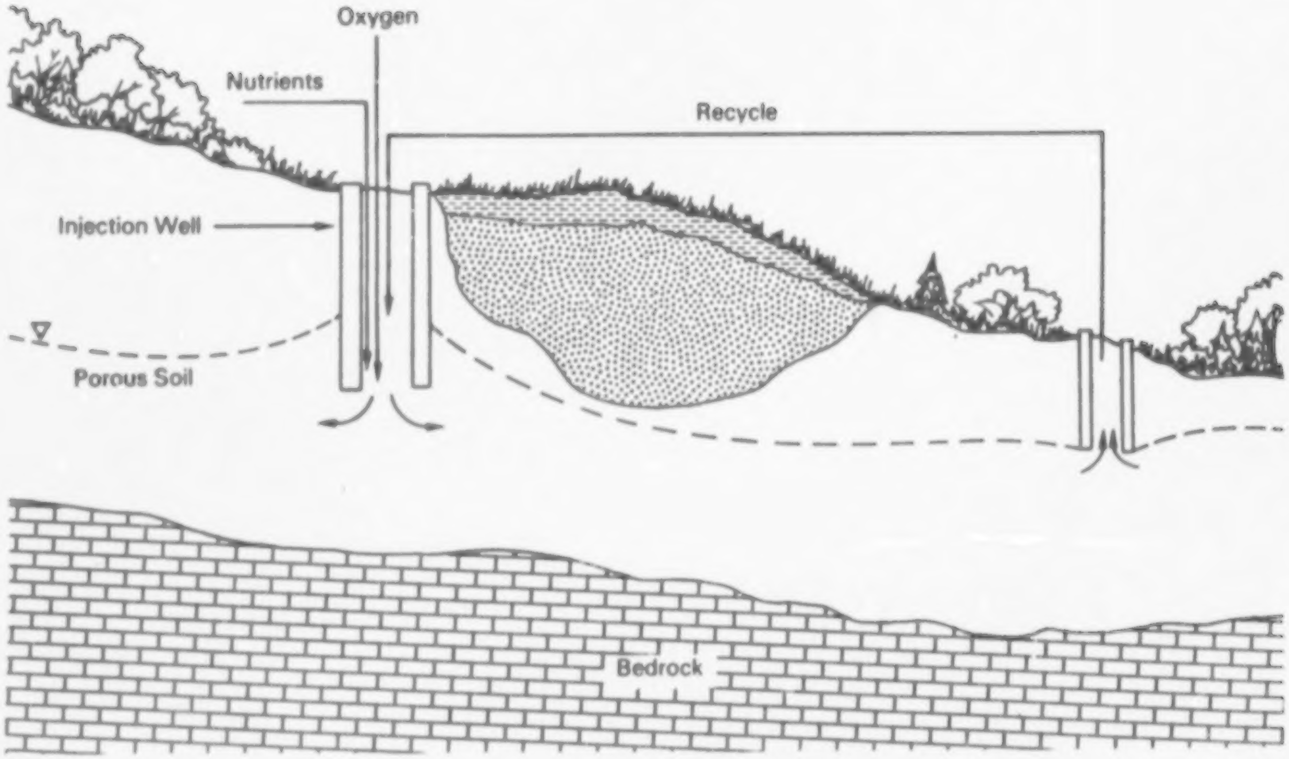

Figure 2.14. Treatment of the contaminated ground water with the bioreclamation technique.

Source: EPA, 1982.

TABLE 2.12. ADVANTAGES/DISADVANTAGES OF THE BIORECLAMATION TECHNIQUE

Advantages	Disadvantages
1. Good for removal of hydrocarbons and a limited amount of organic material from contaminated ground water.[a]	1. Does not remove chlorinated solvents or heavy metals.[a]
2. Environmentally sound.[a]	2. Introduction of nutrients containing phosphate and nitrogen may have adverse effects on the surface water stream located near the treatment site.[a]
3. Fast, safe and economical.[a]	3. Excessive breakdown of equipment such as pumps, compressors, and diffusers may occur, resulting in higher maintenance and operational cost.[a]
4. Inexpensive materials used.[a]	4. Long-term effectiveness of this method is unknown.[a]
5. Good for short-term treatment of contaminated ground water.[a]	5. Bacteria can plug the soil and reduce circulation.[b]
6. Treatment moves with plume.[b]	6. Residues can cause taste and odor problems.[b]
	7. Under certain conditions, such as high concentrations of pollutants, it may be slower than physical recovery methods.[b]

[a] EPA, 1982.

[b] Knox, et al., 1984.

TABLE 2.13. SUMMARY OF HYDROGEOLOGIC GROUND-WATER CONTROL/TREATMENT TECHNOLOGIES

Control/Treatment Technology	Technology Status	Control/Treatment Strategy	Hydrogeologic/Hazardous Constituent Applicability	Additional Remedial Measures	Effectiveness/ Applicability/Comments
IMPERMEABLE BARRIERS					
Slurry Cut-Off Walls (soil-bentonite, cement-bentonite, diaphragm)	Proven (in use but no performance data)		Slurry mixtures incompatible with concentrated organics and highly acidic constituents.	Ground-water pumping (well systems); surface and subsurface collection (interceptor systems); surface sealing; grouting; sheet pile cut-off wall; or synthetic membrane.	Effectiveness determined by wall configuration and associated remedial measures.
- Vertical Configuration					
keyed in			Used if hazardous constituents migrates vertically and horizontally within the aquifer.		Keying in a wall to bedrock is difficult if the bedrock is difficult to excavate or if it is jointed or cracked.
hanging			Used to control floating hazardous constituents i.e. hydro-carbons, petroleum products.		
- Horizontal Configuration		Upgradient diversion			Requires high ground-water gradient, otherwise ground water is apt to overtop wall.
		Downgradient diversion/ interception			Only used for small quantities of upgradient water flowing through the site; waste/wall compatibility is very important.
		Circumferential			Common practice.

(continued)

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TABLE 2.13 (continued)

Control/Treatment Technology	Technology Status	Control/Treatment Strategy	Hydrogeologic/Hazardous Constituent Applicability	Additional Remedial Measures	Effectiveness/ Applicability/Comments
Grout Curtains (particulate, chemical)	Emerging	Upgradient diversion	All hazardous constituents generally compatible. Used as impermeable barrier alone or for sealing fissures, solution channel sand other voids in rock or as water-tight seal for keyedin slurry cut-off walls.	Ground-water pumping (well systems); surface and sub-surface collection (inter-ceptor systems); surface sealing; slurry or sheet pile cut-off wall; or synthetic membrane.	Not often used alone due to cost but practical and efficient for sealing voids in rocks. Ground-water flow can adversely affect the integrity of the grout curtain particularly during construction. Special consideration must be given to rate of ground-water flow and waste compatibility.
Sheet Pile Cut-Off Walls	Imminent	Upgradient diversion Downgradient diversion/ interception	Useful for controlling leachate generation for locations where waste is deposited in contact with a permanent or seasonal water table. Typically used in uniform, loose, boulder-free soil.	Ground-water pumping (well systems); surface and sub-surface collection (inter-ceptor systems); surface sealing; grouting; slurry cut-off wall; or synthetic membrane.	Can not use in very rocky soils. pH of the leachate is of particular importance in determining pile life. Cut-off wall must extend to impermeable strata or bedrock to be effective. Costly.
Block Displacement Method	Imminent	Upgradient diversion Downgradient diversion/ interception	Very useful in stratum where unweathered bedrock or other impermeable strata is not sufficiently near the sur-face for a perimeter barrier (e.g. slurry or sheet pile cut-off wall, grout curtain) to act as an isolator. Slurry (bottom barrier) material incompatible with concentrated organics and highly acidic constituents.	Ground-water pumping (well systems); surface and sub-surface collection (inter-ceptor systems); surface sealing; grouting; slurry or sheet pile cut-off wall; or synthetic membrane.	Places a bottom barrier to hazardous constituent contaminant flow beneath waste site. Lowers watertable inside isolated area. Effectiveness of bottom barrier is based on the permeability of the consolidated slurry material and the thickness of the barrier. Perimeter and bottom barriers should be compatible with in situ soil, groundwater, and hazardous constituent plume characteristics.

(continued)

TABLE 2.13 (continued)

Control/Treatment Technology	Technology Status	Control/Treatment Strategy	Hydrogeologic/Hazardous Constituent Applicability	Additional Remedial Measures	Effectiveness/ Applicability/Comments
WELL SYSTEMS	Proven	Upgradient diversion Downgradient diversion/ interception Extraction/ recharge	Useful where ground-water conditions are stagnent i.e., hydraulic gradient nearly zero and, although more costly, when combinations of fine and textured soils or upward hydraulic gradients make subsurface drainage (interceptor systems) difficult.		Well systems can be used to: (1) manage a plume by containment and/or extraction which includes extracting and treating the ground water and using it to recharge the aquifer, and pumping out the hazaruous constituent plume without the use of recharge; and (2) adjust the water table to prevent ground-water pollution which includes lowering the water table to prevent direct contact with the plume, and upcoming of the water table to act as a barrier to hazardous constituent movement. Effect of long-term pumping on local ground-water levels should be considered.
Well Points			Extract water from shallow, unconfined aquifers.		Only practical for shallow aquifers because of suction lift limits of centrifugal pump. Design should be such that well spacing and drawdown potential of system are sufficient to intercept hazardous constituent plume.
Deep Well Systems			Extract water from aquifers at depths of up to several hundred meters.		Design should be such that well spacing and drawdown potential of system are sufficient to intercept hazardous constituent plume.

(continued)

TABLE 2.13 (continued)

Control/Treatment Technology	Technology Status	Control/Treatment Strategy	Hydrogeologic/Hazardous Constituent Applicability	Additional Remedial Measures	Effectiveness/ Applicability Comments
Recharge Systems					
- Pressure Ridge			Injects water into ground water for upconing of water table to act as a barrier to ground-water flow; also isolation and extraction of hazardous contituents in water.		
- Seepage or Recharge			Water seeps into ground-water table by gravity flow.	Used in conjunction with down-gradient pumping wells.	
SUBSURFACE DRAINS OR INTERCEPTOR SYSTEMS	Proven		Only applicable to shallow releases; usually installed in unsaturated media so that only hazardous constituent (leachate) are collected.		Subsurface drains have two basic applications in the abatement of hazardous constituent release; they either function as relief drains or interceptor drains. Inexpensive relative to other control/ treatment technologies.
- Relief Drains		Upgradient diversion Downgradient diversion/ interception Perimeter	Applicable where hydraulic gradient is almost zero.	Ground-water pumping (well systems).	Lowers water table beneath the site and prevents hazardous constituents from migrating to deeper aquifers.
- Interceptor Drains		Downgradient diversion/ interception			Collects and removes hazardous constituents from ground water.
Collector Drains			Typically used below or near a land disposal facility to intercept leachate leaking through a liner.		Installed perpendicular to ground-water flow.

(continued)

TABLE 2.13 (continued)

Control/Treatment Technology	Technology Status	Control/Treatment Strategy	Hydrogeologic/Hazardous Constituent Applicability	Additional Remedial Measures	Effectiveness/ Applicability/Comments
Interceptor Trenches				Surface sealing (e.g. synthetic membrane).	Installed perpendicular to ground-water flow.
- Active			Ground-water pumped out of backfilled trenches by vertical removal wells or drained by perforated horizontal collector pipes.		
- Passive			Floating hazardous constituents (i.e.petroleum products, hydro-carbons) are removed from open trenches by skimming pumps.		Pumping and skimming processes must be continuous to prevent collected pollutants from seeping into trench walls.
IN SITU TREATMENT					
Permeable Treatment Beds (limestone, activated carbon, glauconitic green sand, zeolite and synthetic ion)	Emerging	In situ treatment Downgradient diversion/ interception due to placement of bed	Applicable to shallow aquifers.		Often only effective for short time because beds lose their reactive capacity or become plugged with solids.
Chemical Injection	Emerging	In situ treatment	Has treated leachate containing cyanide.		Areal spread and depth of hazardous constituents plume must be characterized so that injection wells are properly placed to intercept all contaminated ground water. Can displace contamination due to increased volume.
Bioreclamation	Emerging	In situ treatment Extraction/recharge due to recirculating process of bioreclamation	Effectively applied to removal of hydrocarbon contaminated ground water. Hazardous constituents must be biodegrable; bioreclamation incompatible with certain organic substances e.g., chlorinated solvents.		Requires proper aeration.

PERMIT WRITERS' CHECKLIST

Site Name/Location ______________________________

1. Has applicant undertaken a hydrogeologic investigation of the site in question? (yes or no) ________

2. Does hydrogeologic investigation include the following information (place check beside data provided):

Site Soil Characteristics

- Type ________
- Texture (granular or cohesive) ________
- Grain size distribution and gradation ________
- Moisture content ________
- Permeability ________
- Soil pressure ________
- Porosity ________
- Composition ________
- Compaction ________
- Discontinuities in soil strate (e.g. faults) ________
- Cohesive and consolidation states of individual strata ________
- Degree and orientation of soil stratification and bedding ________
- Location and type of weathered bedrock or solution channels ________
- Other (specify) ______________________________

Ground-Water Characteristics

- Depth to water table ________
- Direction of flow ________
- Rate of flow ________
- pH ________
- Hardness ________
- Salt concentration ________
- Presence of minerals and organics ________

- Concentration of sulfides and calcium ________
- Water pressure ________
- Recharge quantity ________
- Location of neighboring water bodies (e.g. streams) ________
- Other (specify) ____

Aquifer Characteristics

- Use of aquifer ________
- Permeability and thickness of water bearing strata ________
- Transmissivity ________
- Storativity ________
- Specific yield ________
- Depth ________
- Type (confined or unconfined) ________
- Condition (e.g. homogeneous, isotropic, leaky) ________
- Hydraulic gradient ________
- Effective porosity ________
- Identification of recharge and discharge areas ________
- Identification of aquifer boundaries (i.e. areal extent) ________
- Aquiclude characteristics (depth, permeability, degree of jointing, hardness, continuity) ________
- Other (specifiy) ____

Hazardous Constituent Plume Characteristics

- Size ________
- Location ________
- Shape ________
- Hydraulic gradient across plume ________
- Depth to plume ________
- Chemistry and concentration ________
- Velocity ________
- Other (specify) ____

3. Indicate ground-water control/treatment technology under consideration by applicant (specify particular technology(s) beside appropriate category):

- Impermeable barrier ________
- Well system ________
- Interceptor system or subsurface drain ________
- In situ treatment ________

4. Control/treatment technology(s) strategy and location: (Check strategy/location and indicate number of control/treatment units)

- Upgradient diversion ________
- Downgradient diversion/interception ________
- Surrounding site ________
- Extraction/recharge ________
- In situ treatment ________
- (• Source control ________)

5. Purpose of control/treatment technology: (check appropriate purposes)

- Control ground-water flow ________
- Treat ground water ________
- Isolate hazardous constituent plume ________
- Extract hazardous constituent plume ________
- Replenish ground water ________
- Adjust water table ________
- Control subsurface flow of hazardous constituents ________
- Neutralize, precipitate or destroy hazardous constituents ________
- Other (specify) ____

6. Is control/treatment technology applicable to site terms of: (yes or no; refer to appropriate control/treatment technology discussions).

- Implementability ________
- Effectiveness ________
- Reliability ________
- Compatability of hazardous constituent (plume) with technology ________
- Site's subsurface characteristics ________

7. Environmental concerns associated with this control/treatment technology: (check where applicable)

- Subsidence ________
- Decrease in well yield of adjacent well field ________
- Drawdown of adjacent surface water bodies ________
- Induced hazardous constituent migration to new pathways ________
- Other (specify) ________________________________

TREATMENT TECHNOLOGIES

Several technologies are available to treat contaminated ground water after being withdrawn from the subsurface. Treatment technologies are capable of removing various percentages of certain hazardous constituents. In selecting an appropriate treatment method, the following factors must be considered: the type(s) of hazardous constituents to be removed; the amount of water to be treated; the initial concentration(s) of hazardous constituents; and the desired final concentrations(s) of hazardous constituents. Table 2.14 lists several treatment techniques which are available, and indicates the types of contaminants for which these techniques can be used most effectively. Brief descriptions of the most commonly used treatment technologies are given in the following subsections.

Carbon Adsorption

Carbon adsorption can be an effective process for the removal of dissolved organic compounds from contaminated ground water. Compounds which are effectively treated by carbon adsorption include chlorinated pesticides, phenols, aliphatic chlorinated hydrocarbons, and aromatics (such as benzene, toluene, and xylene) (Chillingworth, 1981). The efficiency of carbon adsorption in removing various organic compounds is presented in Tables 2.15 and 2.16

Carbon adsorption can be designed for either column or batch applications however, ground-water treatment generally utilizes carbon columns. In column applications, adsorption involves the passage of contaminated water through a bed of activated carbon which selectively adsorbs the hazardous constituent (adsorbate) onto the carbon (adsorbent). When the activated carbon has been utilized to its maximum adsorptive capacity (exhaustion), it is then removed for disposal, destruction, or regeneration.

The carbon columns can be designed such that flow is downward (downflow) through the bed, either under pressure or gravity flow (fixed bed), or the flow can be upward (upflow) through a packed or expanded bed. For treating contaminated ground water, a common adsorber configuration would be to place

TABLE 2.14. STATE-OF-THE-ART TECHNIQUES FOR TREATING COMMON GROUND-WATER CONTAMINANTS

Candidate Treatment Technologies	Common Types of Ground-Water Contaminants			
	Heavy "Metal" Cations	Heavy "Metal" Anions	Non-Metallic Toxic Anions	Organics
Air Stripping				X
Carbon Adsorption	X	X	X	X
Chemical Oxidation	X		X	X
Chemical Reduction	X	X		
Distillation				X
Electrodialysis	X	X	X	
Electrolysis	X	X	X	
Evaporation			X	X
Filtration	X	X	X	X
Flocculation	X	X		
Hydrolysis				X
Ion Exchange	X	X	X	X
Liquid Ion Exchange	X	X	X	
Neutralization	X	X	X	X
Ozonation	X	X	X	X
Precipitation	X	X		
Resin Adsorption				X
Reverse Osmosis	X	X	X	X
Sedimentation	X	X		
Steam Stripping				X
Ultrafiltration	X	X	X	X

Source: Adapted from Arthur D. Little, Inc., 1977.

TABLE 2.15. OPERATING RESULTS AND CHARACTERISTICS OF CARBON ADSORPTION SYSTEMS FOR INFLUENT CONTAMINANTS AT μg/l LEVELS

System Number	Contaminants	Typical Influent Concentration μg/l	Typical Effluent Concentration μg/l	Carbon Type	Flow GPM	Total Contact Time in Minutes	Carbon Usage (lbs/1,000 gallons)
1	Perchloroethylene	10	<1	Virgin F-300	200	27	0.5
	Trichloroethylene	5	<1				
2	Trichloroethane	143	<1	Virgin F-300	350	15	<0.44
	Tetrachloraethylene	8.4	<1				
	Trichloroethylene	26.3	<1				
3	Di-isopropylether	56	<1	Virgin F-300	900	12	0.4
	Trichloroethylene	64	<1				
4	Trichloroethylene	8-15	<1	Virgin F-300	800	27	<0.46
5	Di-isopropyl Methyl Phosphonate	1,250	<50	Reactivated	175	30	0.7
	Dicyclopentadiene	450	<10				
6	Chloroform	20	<2	Reactivated	30	160	
7	Trichloroethylene	50	<1	Virgin F-300	80	120	1.45
8	DDT	1	<.05	Reactivated	70	75	0.55
	DDE	1	<.05				
	DDD	1	<.05				

Source: Kaufmann, 1982.

TABLE 2.16. OPERATING RESULTS AND CHARACTERISTICS OF CARBON ADSORPTION SYSTEMS FOR INFLUENT CONTAMINANTS AT mg/l LEVELS

System Number	Contaminants	Typical Influent Concentration mg/l	Typical Effluent Concentration mg/l	Carbon Type	Flow GPM	Total Contact Time in Minutes	Carbon Usage (lbs/1,000 gallons)
1	Methylene Chloride	21	.1	Reactivated	20	262	3.9
	1,1,1 Trichloroethane	25	1				
2	Phenol	63	1	Reactivated	80	66	5.8
	Orthochlorophenol	100	1				
3	Phenol	32-40	0.1	Reactivated	875	60	2.1
	Vinylidine Chloride	2-4	0.1				
4	Ethyl Acrylate	200	1	Reactivated	300	52	13.3
5	Chloroform	3.7	1	Reactivated	40	130	11.6
	Carbon Tetrachloride	72.9	1				
	Trichloroethylene	4.3	1				
	Perchloroethylene	51.3	1				
6	Perchloroethylene	9	1	Virgin F-300	120	44	2.4
	Trichloroethylene	1	1				
	Cis-1,2 Dichloroethylene	1	1				
7	1,1,1 Trichloroethane	1	1	Reactivated	25	228	1.0
8	Dichloroisopropylether	1	1	Reactivated	2,250	20	0.41
	Dichloroethylether	1.2	1				

Source: Kaufmann, 1982.

two downflow pressue adsorbers in series. The lead adsorber effects the adsorption until it is exhausted. It is then taken off line for regeneration, and the flow is switched to the second column in series. Following regeneration, the fresh column is placed on-stream at the end of the sequence, and the process is repeated.

Factors to consider in the design of a carbon adsorption system are carbon exhaustion (usage) rate, contact time, hydraulic loading rate, and column size. Carbon exhaustion rate is very important since it dictates how often spent carbon must be replaced by new or regenerated carbon. It is defined as the weight of carbon required for treating a specified volume of water to a specific effluent quality, and it will depend on several factors includng the effluent requirements and the type and concentration of the contaminant (Troxler, 1983). Examples of carbon usage rates for removal of volatile organics from ground water were previously given in Tables 2.15 and 2.16.

Tables 2.15 and 2.16 also present superficial contact times for several ground water treatment applications. As is evident, the contact times required for treating hazardous constituent concentrations at the μg/l level are generally lower (12-160 minutes) than for those systems treating hazardous constituent concentrations at the mg/l level (20-202 minutes). Contact time will also depend on the particular contaminant and the effluent requirements.

The hydraulic loading rate will depend on the contact time, the head loss in the adsorber, the dimensions of the adsorber, and the carbon particle size. It can vary from less than 0.5 gpm/ft up to 8 gpm/ft^2. Fifty percent of the granular activated carbon (GAC) columns evaluated in one study utilized hydraulic loading rates of less than 1.5 gpm/ft^2 (Troxler, 1983).

Carbon column dimensions are also highly variable and depend on the two previous parameters. Heights are typically 20 to 40 feet, and typical diameters are less than 12 feet (Troxler, 1983).

The effectiveness of GAC in removing a variety of organics was presented earlier in Tables 2.15 and 2.16. Adsorption efficiencies are affected by both the characteristics of the hazardous constituent and the characteristics of the aqueous waste streams in which they are contained.

Characteristics of the hazardous constituent which affect adsorption include polarity, molecular weight, solubility, and molecular structure. In general, non-polar, high molecular weight organics with limited solubility are preferentially adsorbed. Also, branched-chain compounds are generally more adsorbable then straight-chain compounds.

Characteristics of the aqueous stream which affect adsorption efficiency include: pH, temperature, suspended solids concentration, and oil and grease concentration. The effect of pH will vary from compound to compound but, in general, the compound will adsorb at the pH which imparts the least polarity to the molecule. For example, phenol is a weak acid and will consequently be adsorbed at low pH, while amines which are basic will be adsorbed more easily at higher pH values. Because adsorption is an exothermic process, increased adsorption will occur when temperatures are increased (Lyman, 1978; Troxler, 1983).

For an aqueous stream to be treated by carbon adsorption, the suspended solids concentration should generally be less than 50 ppm, and the concentration of oil and grease should be less than 10 ppm. Consequently pretreatment, usually granular filtration, is often required to prevent excessive headloss in the bed due to clogging by suspended solids or oil and grease.

Granular Filtration

Granular filtration techniques can be used to remove suspended solids from the aqueous phase. It is often employed as a pretreatment technique (intermediate process) or as a final polishing step. The two basic types of filter systems are the rapid sand filter and the slow sand filter. Only rapid sand filters, however, are appropriate for ground-water treatment applications. Table 2.17 describes the general features of rapid sand filters.

The apparatus for the rapid sand filtration technique consists of a bed of sand which is supported by an underdrain system that collects the filtrate. As the filtration process proceeds, suspended particles become trapped on top of and within the bed, which reduces the efficiency of the process. Eventually, it becomes necessary to remove these solids from the filter media.

TABLE 2.17. GENERAL FEATURES OF CONSTRUCTION AND OPERATION OF RAPID SAND FILTERS

	Rapid Sand Filters
Rate of filtration	100 to 125 to 300 mgad[a]
Size of bed	Small, 1/100 to 1/10 acre
Depth of bed	18 in. of gravel; 30 in. of sand, or less; not reduced by washing
Size of sand	0.45 mm and higher; coefficient of nonuniformity 1.5 and lower, depending on underdrainage system
Grain size distribution of sand in filter	Stratified with smallest or lightest grains at top and coarsest or heaviest at bottom.
Underdrainage system	(1) Perforated pipe laterals discharging into pipe mains; (2) porous plates above inlet box; (3) porous blocks with included channels
Loss of head	1 ft inital to 8 or 9 ft final
Length of run between cleanings	12 to 24 to 72 hr
Penetration of suspended matter	Deep
Method of cleaning	Dislodging and removing suspended matter by upward flow or backwashing, which fluidizes the bed. Possible use of water or air jets, or mechanical rakes to improve scour

(continued)

TABLE 2.17 (continued)

	Rapid Sand Filters
Amount of wash water used in cleaning sand	1 to 4 to 6% of water filtered
Preparatory treatment of water	Coagulation, flocculation, and sedimentation
Supplementary treatment of water	Chlorination
Cost of construction, U.S.A	Relatively low
Cost of operation	Relatively high
Depreciation cost	Relatively high

[a] 125 mgad = 2 gpm per sq ft = 16 ft per hr = 125 m per day.

Source: Fair, et. al., 1968.

Regeneration of the filtration media is accomplished by means of a "back-washing technique. During this step, the underdrainage system doubles as a water distribution system. Water rises into the filter bed in the reverse direction of the original flow causing the filter bed to become fluidized. Commonly used methods for scouring the filtering media include:

- High-Velocity Wash - Wash water is forced upward through the filter bed at a velocity high enough to cause the filter bed to become fluidized and turbulent.
- Surface Scour - Jets of water are directed into the fluidized bed causing increased turbulence.
- Air Scour - Air is blown upward through the bed either before or during fluidization of the bed.
- Mechanical Scour - The fluidized bed is stirred using a mechanical apparatus.

During the scouring process the solids become dislodged from the sand and are discharged in the spent wash cycle. The bed is then allowed to resettle. The coarser, heavier grains tend to settle at the bottom while the finer, lighter grains remain at the top. Thus, the bed becomes stratified.

Various modifications to the sand filtration unit may be employed. One type of modification is the dual-media filtration unit which has a filter bed consisting of a layer of anthracite underlain by a layer of sand. In multimedia filtration, several layers of different materials are used for the filtration media. Filter materials may include natural silica sand, crushed anthracite, (hard) coal, crushed magnetite (ore), and garnet sands.

Filtration systems can consist of multiple compartment concrete or steel units aligned horizontally or vertically. The flow through the filtration units occurs by using the available head from the previous treatment unit, or by pumping to a flow-split box and then using the effects of gravity to allow flow to the filter cells. Pressure filters use pumping to increase the available head.

Ion Exchange

Ion exchange is a reversible process in which an interchange of ions occurs between a solution and an essentially insoluble solid in contact with the solution. Both natural and synthetic substances can act as ion exchangers. Natural ion exchange materials usually consist of clays or zeolites (Skoog & West, 1979). Zeolites have been used effectively in the removal of ammonia from wastewater (Metcalf & Eddy, 1972). Synthetic resins are used more commonly because of their durability (EPA, 1982). Synthetic ion exchange resins are composed of high molecular weight, polymeric materials containing a large number of ionic functional groups per molecule (Skoog & West, 1979).

Cation exchange resins exchange only positively charged hazardous constituent species from contaminated ground water. The extent to which removal of anions and/or cations occurs depends on the equilibrium that is established between the ions in the aqueous phase and those in the solid phase (EPA, 1982). The preference of one kind of exchangeable ion over another depends on the nature and volume of the ion, the type of resin and its saturation, and the ion in the contaminated ground water (EPA, 1982). As a general rule, ions with a higher charge will form more stable salts with the exchanger than those with a lower charge, and hence polyvalent species can frequently be selectively removed from a solution of monovalent ions (species).

The ion exchange process may be operated using a batch or continuous technique (Metcalf & Eddy, 1972; EPA, 1982; EPA, 1980). In a batch process, the ion exchange resin is stirred with the water to be treated until the reaction is complete. The spent resin is removed by settling and is subsequently regenerated and reused (Metcalf & Eddy, 1972). In a continuous process, the exchange material is placed in a bed or packed column, and the water to be treated is passed through it (Metcalf & Eddy, 1972). The continous ion exchange process is operated in a cycle of four steps: service (exhaustion), backwash, regeneration, and rinse (EPA, 1980). Initially, the water to be treated is passed through the ion exchanger until the active sites in the exchanger are partially or completely used up ("exhausted") by that ion (EPA, 1980). During the backwash step, the bed is washed (generally with water) in the reverse direction of the service cycle in order to expand and resettle the resin bed. The exchanger is the "regenerated" by passing a concentrated solution of the ion originally associated with it through the resin bed. The rinse step removes the excess regeneration solution prior to the next service step (EPA, 1980).

With the continuous process, three modes of operation are possible: cocurrent fixed bed, countercurrent fixed bed, and countercurrent continuous (EPA, 1982). The fixed bed ion exchange technique is most often used to treat contaminated ground water. Variations of the fixed bed exchange mode include mixed beds and the use of exchange columns in a series. When a number of beds are used in series, the upstream bed can be detached, regenerated, and reattached at the downstream end (similar to a countercurrent stream) (EPA, 1982). A "staged" fixed bed technique is often employed to allow more efficient use of the regenerant materials.

Ion exchange can be successfully used to remove cationic and anionic metallic elements, halides, cyanides, nitrate, carboxylics, sulfonics, and some phenols. However, there are limitations in the use of this technique for ground-water treatment. Ion exchange is not suitable for removal of high concentrations of exchangeable ions, because the resin material is rapidly exhausted during the exchange process and costs for regeneration become prohibitively high. The upper concentration limit for exchangeable ions for efficient operations is about 2500 mg/l expressed as calcium carbonate (or 0.5 equivalents/l). Another limitation of ion exchange is that pretreatment of the ground water is often necessary because certain hazardous constituents decrease the effectiveness of the resin. Also, certain organics (especially aromatics) become irreversibly absorbed by the resin. Oxidants (such as chromic or nitric acid) can also damage the resin. Prefiltering the ground water and/or using scavenger exchange resins can alleviate these problems, at an additional cost however.

Chemical Oxidation

Chemical oxidation is a ground-water treatment technology that can be used to remove ammonia, decrease the concentration of residual organics, and to decrease the bacterial and viral content of ground water (Metcalf & Eddy, 1972). Additional applications include the conversion of organic and inorganic substances into less harmful or into more desirable forms, the removal of iron and manganese, and the removal of tastes and odors (Sundstrom and Klei, 1979).

Oxidation-Reduction reactions (or "Redox" reactions) are those in which the oxidation state of at least one reactant is raised while that of another is lowered. The oxidation states of the reactants change as a result of electron transfer. An oxidant is an electron acceptor and a reductant is a substance which donates electrons.

Several oxidizing agents can be used in the treatment of contaminated ground water. The more commonly used oxidants are listed in Table 2.18. The extent of oxidation that occurs is affected by the dosage of the oxidant, the pH of the reaction medium, the oxidation potential of the oxidant, and whether or not stable intermediates are formed (EPA, 1980).

The first step of the chemical oxidation process usually involves adjusting the pH of the solution to be treated. Next, the oxidizing agent is added. Mixing is utilized to contact the oxidizing agent and the ground water. More concentrated solutions require cooling due to the heat that is generated during mixing. Reaction times vary, but are generally not more than a few minutes for most commercial-scale installations. Usually, additional time is allowed to ensure complete mixing and oxidation. Upon completion of the oxidation reaction, the oxidized solution is then generally subjected to another form of treatment to precipitate and remove any insoluble oxidized material, metals, or other residues. The excess oxidizing agent (both reacted and unreacted) may also have to be removed.

TABLE 2.18. TREATMENT APPLICATIONS OF THE MOST COMMONLY USED OXIDANTS

Oxidant	Hazardous Constituent
Ozone	--
Air (atmospheric oxygen)	Sulfites ($SO_3^=$) Sulfides ($S^=$) Ferrous iron (Fe^{++}) (very slow)
Chlorine gas	Sulfide Mercaptans
Chlorine gas and caustic	Cyanide (CN^-)
Chlorine dioxide	Cyanide Diquat Paraquat pesticides
Sodium hypochlorite	Cyanide Lead
Calcium hypochlorite	Cyanide
Potassium permanganate	Cyanide (organic odors) Lead Phenol Diquat Paraquat pesticides
Oxidants that are present in trace quantities only	Organic sulfur compounds Rotenone Formaldehyde
Permanganate	Manganese
Hydrogen peroxide	Phenol Cyanide Sulfur compounds Lead
Nitrous acid	Benzidene

Source: EPA, 1980.

The major disadvantage of chemical oxidation for ground-water treatment is that it introduces new metal ions into the effluent. Depending on the levels of these new ions, additional treatment techniques, such as filtration or sedimentation, may often be necessary. For most chemical oxidations, there will be a residue for disposal unless the concentration of the hazardous constituent is so low that the oxidant products (if any) and the oxidized constituents can be carried away with the effluent. The hazardous constituent sludge which results from the oxidation treatment of cyanides when iron and certain other transition metal ions are present (e.g., ferrocyanide) cannot be easily treated with further oxidation.

Reverse Osmosis

Reverse Osmosis is a treatment technique used to remove dissolved organic and inorganic materials, and to control amounts of soluble metals, TDS, and TOC (Metcalf & Eddy, 1972; EPA, 1980).

The process of reverse osmosis involves filtering the contaminated ground water through a semipermeable membrane at a pressure greater than the osmotic pressure caused by the dissolved materials in the water. Operating pressures generally range from atmospheric to 1500 psi (Metcalf & Eddy, 1972; EPA, 1980).

The semipermeable membrane can be either in the form of a sheet or tube (Sundstrom and Klei, 1979). As shown in Figure 2.15, the ground-water solution (termed the "feed") flows over the surface of the membrane, with the treated water (termed the "concentrate") containing the removed materials leaving the membrane (Sundstrom and Klei, 1979; EPA, 1980).

The amount of material which can be removed using the reverse osmosis technique is dependent on the membrane type, operating pressure, and the specific pollutant of concern (EPA, 1980). Multicharged cations and anions are easily removed from the wastewater with this technique. However, most low molecular weight dissolved organics are not removed or are only partially removed with this method.

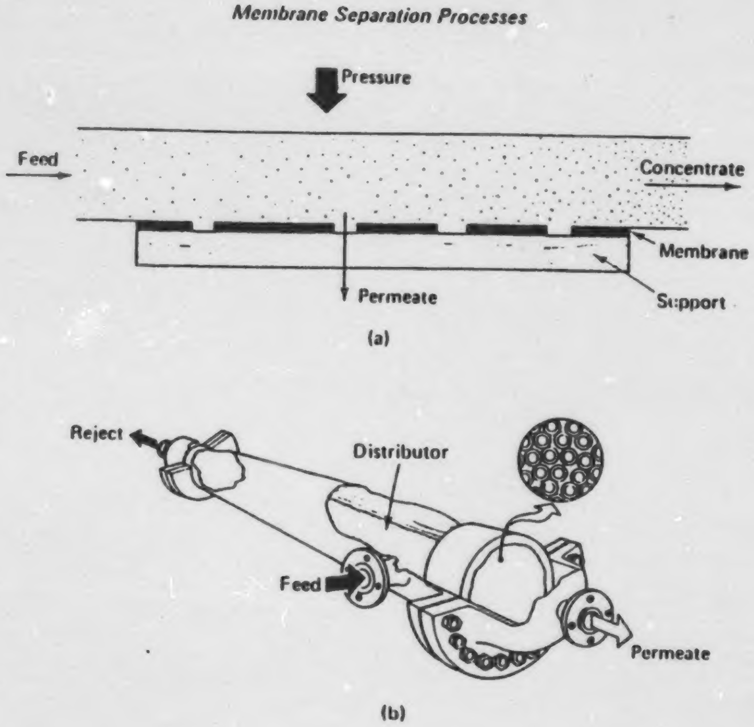

Figure 2.15. Membrane processes using a pressure driving force in (a) plane and (b) tubular designs.

Sources: Sundstrom and Klei, 1979.

During manufacture, the semipermeable membrane is heat-treated in such a way that the rate at which water can be produced is fixed. Colloidal and organic matter can clog the membrane surface, thus reducing the efficiency of the process. Also, the low-solubility salts will precipitate on the membrane and reduce the level of product water. Pretreatment techniques such as activated carbon adsorption, chemical precipitation, and filtration, may need to be used. Operating costs for membrane systems are a direct function of the concentration of the impurity to be removed.

Air Stripping

Air stripping, when applied to the treatment of contaminated ground water, is the process of driving volatile compounds from the aqueous to the gaseous phase. Air stripping is most commonly achieved in a packed tower in which air and water flow countercurrent to one another with the water flowing downward over the packing as a thin flim, while the air flows upward carrying away the volatile constituents.

Important factors to consider in the design of a stripping column include: the type and size of packing, air-to-water ratio, pressure drop in the column, and the height and diameter of the column. The packing material used will depend on resistance to corrosion and ease of handling, and for water treatment is usually plastic saddles or rings. The packing material will influence both the head loss in the column and the mass transfer rate of the contaminants. Once a packing material is selected and water flow rate is known a number of air-to-water ratios, tower diameters and tower heights may be used to achieve a given removal of a certain compound.

Models relating the above parameters to removal efficiency are presented in several papers which should be consulted if further information is desired (Ball et al., 1984; Roberts et al., 1985; Gross and Termaath, 1984; Crittenden, 1984).

Air stripping can be effective either as an alternative to carbon adsorption or as a complementary process to adsorption. As an alternative, it can be only 20 to 30 percent of the cost of adsorption, and still achieve equivalent results (Shilling, 1985) for removal of volatile compounds. In addition, many compounds which are difficult to remove by carbon adsorption are effectively removed by air stripping. These include trihalomethanes and other halogenated methanes and ethanes. As a complementary process preceeding adsorption, air stripping may decrease the organic loading on the carbon adsorbent thereby decreasing the carbon requirements, and it may also remove contaminants which would not be removed by adsorption (McCarty, 1979).

A disadvantage of air stripping is that the hazardous constituents which are stripped from solution will be released into the air. In many cases this may not present a problem since the concentration of hazardous constituents in the water is in the μg/l range, and if a high air-to-water ratio is used, this concentration will be lowered even further by dilution and dispersion. In other cases, however, it may be necessary to control air emissions by employing a vapor treatment process such as carbon adsorption or incineration.

Compounds susceptible to removal by air stripping include trihalomethanes, chlorinated benzenes, some aromatic hydrocarbons, and even some pesticides. In general, the amenability of an organic compound to be stripped from a dilute aqueous solution can be determined by the equilibrium between the concentration of the organic in the aqueous phase and the concentration in the air. This relationship is quantified by the Henry's Law Constant. The higher the value, the greater the potential for the compound to be air stripped. McCarty (1979) has indicated that compounds with a Henry's Law Constant greater than 1×10^{-3} atm-m^3/mol should be amenable to air stripping. The Henry's Law Constants for several compounds on the U.S. EPA priority pollutant list are given in Table 2.19.

The effectiveness of removal for various compounds will depend on the design of the column, but with proper design 90-100 percent removal of compounds which are amenable to air stripping is possible.

TABLE 2.19. CALCULATED HENRY'S LAW CONSTANTS AT 20°C FOR ORGANIC COMPOUNDS

Compound	H atm m^3/mol
Vinyl chloride	6.4
Dichlorofluoromethane	2.1
1,1-dichloroethylene	1.7×10^{-1}
1,2-dichloroethylene	1.7×10^{-1}
Trichlorofluoromethane	1.1×10^{-1}
Methyl bromide	9.3×10^{-2}
Toxaphene	6.3×10^{-2}
Carbon tetrachloride	2.5×10^{-2}
Tetrachloroethylene	2.3×10^{-2}
Chloroethane	1.5×10^{-2}
beta-BHC	1.1×10^{-2}
Trichloroethylene	1.0×10^{-2}
Methyl chloride	8.0×10^{-3}
PCB (Aroclor 1260)	6.1×10^{-3}
1,2-trans-dichloroethylene	5.7×10^{-3}
Ethylbenzene	5.7×10^{-3}
Toluene	5.7×10^{-3}
1,1-dichloroethane	5.1×10^{-3}
Benzene	4.6×10^{-3}
Chlorobenzene	4.0×10^{-3}
1,1,1-trichloroethane	3.6×10^{-3}
Chloroform	3.4×10^{-3}
PCB (Aroclor 1248)	3.0×10^{-3}
1,3-dichlorobenzene	2.7×10^{-3}
Methylene chloride	2.5×10^{-3}
Heptachlor	2.3×10^{-3}
PCB (Aroclor 1254)	2.3×10^{-3}
1,4-dichlorobenzene	2.1×10^{-3}
Aldrin	2.1×10^{-3}
1,2-dichloropropane	2.0×10^{-3}
1,2-dichloropropylene	2.0×10^{-3}
Alpha-BHC	2.0×10^{-3}
1,2-dichlorobenzene	1.7×10^{-3}
Anthracene	1.4×10^{-3}
1,2-dichloroethane	1.1×10^{-3}
Hexachloroethane	1.1×10^{-3}
1,1,2-trichloroethane	7.8×10^{-4}
Bromoform	6.3×10^{-4}
PCB (Aroclor 1242)	4.9×10^{-4}
1,1,2,2-tetrachloroethane	4.2×10^{-4}
Naphthlene	3.6×10^{-4}
Fluorene	2.1×10^{-4}

(continued)

TABLE 2.19 (continued)

Compound	H atm m^3/mol
Acenaphthene	1.9×10^{-4}
Phenenthrene	1.3×10^{-4}
Bis(2-chloroisopropyl) ether	1.1×10^{-4}
Acrolein	9.7×10^{-5}
2-nitrophenol	7.6×10^{-5}
Acrylonitrile	6.3×10^{-5}
Di-n-butyl phthalate	6.3×10^{-5}
2,4-dichlorophenol	4.2×10^{-5}
4,4'-DDT	3.4×10^{-5}
2-chlorophenol	2.1×10^{-5}
Nitrobenzene	1.1×10^{-5}
Isophorone	4.2×10^{-6}
Pentachlorophenol	2.1×10^{-6}
Dimethyl phthalate	4.2×10^{-7}
Lindane	3.2×10^{-7}
Phenol	2.7×10^{-7}
Dieldrin	1.7×10^{-7}
4,6-dinitro-o-cresol	1.7×10^{-7}

Source: EPA, 1978b.

SECTION 3

CASE STUDIES

INTRODUCTION

GCA conducted a search for case studies which would demonstrate how to select and implement corrective measures for releases to ground water from SWMUs. Approximately 100 sites were reviewed to develop a list of sites for potential case study analysis. Information was obtained from several data sources including EPA Headquarters, EPA Regional offices, and literature searches.

The site review focused on finding examples of sites where remedial responses were either ongoing or completed. Site Selection Worksheets were completed for sites which met this initial criteria. The worksheet (shown in Figure 3.1) contained information which was used to screen the sites for potential case study evaluations.

The criteria used for final selection of case studies included:

- availability and completeness of site information and monitoring data;
- types of remedial measures implemented;
- types of wastes and hazardous constituents present at the facility;
- site characteristics;
- geographic locations; and
- waste management practices.

WORKSHEET FOR SCREENING CASE STUDIES

SITE NAME

LOCATION

TYPE OF FACILITY

SIZE OF SITE/DISPOSAL AREA

YEARS OF OPERATION/DISCOVERY OF RELEASE (How & when release discovered)

TYPES OF RELEASES

TYPE OF WASTE DISPOSED/HAZARDOUS CONSTITUENTS PRESENT

MEDIA CONTAMINATED

CLIMATE

TOPOGRAPHY

SOILS

Figure 3.1. Worksheet for Screening Case Studies

GEOLOGY

HYDROLOGY (Ground Water & Surface Water)

RESPONSE ACTIONS (Including Designed and Implemented)

MONITORING DATA AVAILABLE

SUCCESS/FAILURE OF REMEDIATION (Removal Efficiency, Containment Effectiveness)

Figure 3.1. (continued)

In reviewing potential case studies, those case studies that were designated as being most representative of a variety of the above criteria and constituents of each criterion were selected.

A list of the selected sites and a summary of the remedial responses at these sites is presented in Table 3.1. Case studies were prepared using the outline shown in Figure 3.2. These case studies are presented below.

GILSON ROAD SITE - NASHUA, NEW HAMPSHIRE

Facility Description

The 6-acre site was used as a sand and gravel borrow pit during the 1950s and 1960s. By the late 1960s most of the sand had been removed. The owner/operators began illegally disposing demolition debris, domestic refuse, chemical wastes, and sludges to fill the excavation area. In 1979, after reports of heavy odors heavy odors in a brook adjacent to the site and subsequent detection of hazardous constituents in a nearby private well, a court order was issued to restrain the owner/operators from further disposal operations at the site. The site is currently on the list of EPA Superfund sites.

Site Characteristics

Soils--

Soils at the site are stratified, unconsolidated glacial deposits consisting primarily of two permeable, interfingering units. These two units consist mostly of fine to medium sands or fine to coarse sands and gravels, with total thicknesses ranging from 20 to 90 feet. The permeable sands overly a thin sequence of glacial till having a maximum thickness of 12 feet. The till is very dense and contains mixtures of unstratified silt, sand, and gravel.

TABLE 3.1. TYPES OF RELEASE(S) AND REMEDIAL ACTION(S) IMPLEMENTED AT SELECTED SITES

Site Name/ Location	Type of Facility	Hazardous Constituents Present	Type(s) of Release(s)	Remedial Action(s)
Gilson Road/ Nashua, NH	Illegal dump site (6 acre)	Metals and organics (chloroform, methylene chloride, ethylene chloride, TCE, MEK toluene, diethylether, acetone, tetrahydrofurans)	Ground water	o Drums Removed o Sludges disposed of onsite in a double-lined landfill o Slurry wall installed o Constucting ground water treatment-reinjection system.
Llangollen Army Creek Landfills/ New Castle, DE	Landfill (50 acres)	Metals and organics (Fe, Mn, Cr, Be, Pb, Ni, Zn, As, TCE chloroform, 1,2-dichloroethane)	Ground water, surface water	o 12 recovery wells installed. Ground water pumped without treatment to nearby stream o Under consideration are: grading, capping, barrier wall, and recovery well relocation.
Rocky Mountain Arsenal/ Denver, CO	Arsenal manufacturing chemical warfare products and pesticides (unlined waste lagoons, storage areas, and manufacturing plant areas)	Pesticide residues, toxic metals, solvents	Ground water	o 3000 ft interceptor trench installed o Wastes from the trench are collected and treated

(continued)

TABLE 3.1 (continued)

Site Name/ Location	Type of Facility	Hazardous Constituents Present	Type(s) of Release(s)	Remedial Action(s)
Stringfellow/ Riverside, CA	Toxic industrial disposal site (surface impoundments, 17 acres)	H_2SO_4, HNO_3, HCl, 50% DOT, TCE, Zn, Hg, Cr, chloroform, chlorobenzene	Ground water	o Excavation o Grout curtain o Clay core barrier and drain o Neutralization and grading o Two interceptor wells
Unknown Name/ Gulf Coastal Plain	Landfill facility (pond liner punctured, leakage occurred)	Petrochemical industrial organics	Ground water-shallow aquifer	o Submersible pump ground-water recovery system o Ground-water model developed o Installation of recharge pit beneath surficial clays o Installation of french drain/jet educator well withdrawal system
Whitmoyer Laboratories (Myerstown,PA)	Wastewater generated by the manufacturing plant treated with lime; slurry disposal in an unlined lagoon	Arsenic	Soils, ground water, surface water	o Ground-water treatment and recovery (counter-pumping) o Excavation of contaminated sludges and soils o Concrete storage bins

OUTLINE FOR CASE STUDIES WRITE-UP

I. FACILITY DESCRIPTION
  A. TYPE OF SWMU/SYSTEM DESIGN (Including any leak detection and/or monitoring system)
  B. YEARS OF OPERATION
  C. TYPE OF WASTES RECEIVED/DISPOSED
  D. SIZE OF SITE/DISPOSAL AREA
  E. ANY PREVIOUS OPERATIONS AT THE SITE/SITE BACKGROUND
  F. REGULATORY & LEGAL STATUS (NPL, CERCLA, etc.)

II. SITE CHARACTERISTICS
  A. CLIMATE
  B. TOPOGRAPHY
  C. SOILS
  D. GEOLOGY
  E. HYDROLOGY (Ground Water & Surface Water)

III. RELEASES
  A. TYPES/CAUSES OF RELEASES
  B. MECHANISMS FOR DETECTION (Include how & when release was detected)
  C. EXTENT OF CONTAMINATION & HAZARDOUS CONSTITUENTS PRESENT (Include media contaminated, and area or volume of contamination)

IV. REMEDIAL ACTIONS
  A. RESPONSE
    1. IMPLEMENTED
    2. UNDER CONSTRUCTION
    3. DESIGNED/CONCEPTUALIZED
    4. MONITORED/TESTED
  B. SUCCESS/FAILURE OF REMEDIATION (Include summary of results from available monitoring data)

Figure 3.2. Outline for Case Studies Write-Up

Geology--

The predominant bedrock type in the site area is of the Merrimack Formation (a metamorphic rock group of Silurian Age), which includes slates, phyllites, and schists. The average depth to the bedrock is approximately 25 feet. Results of site geologic investigations indicated that the bedrock was slightly weathered and moderately fractured including both horizontal and near vertical joints up to 1/2-inch in width. Some of the fractures were partially filled with sand and/or clayey silt. There is evidence that the fractured rock beneath the site is somewhat permeable.

Hydrology--

The site is located less than 1000 feet from Lyle Reed Brook, a small stream tributary to the Nashua River. Any surface discharge from the site would likely flow into this brook which has a total drainage area of about 1.5 sq. miles. The flow from Lyle Reed Brook enters the Nashua River about seven miles upstream from its confluence with the Merrimack River.

Ground water beneath the site occurs under unconfined or water-table conditions in the permeable stratified sands and gravels. It probably also occurs under semi-confined conditions in secondary fractures in the bedrock. The principal direction of the ground water flow appears to be northwest (toward Lyle Reed Brook). Regional flow is northwest toward Nashua River, which is the ultimate sink for ground water leaving the disposal site. The average depth to ground water is approximately 10 ft. Seasonal water table fluctuations at the Gilson Road site are relatively small. Prior to remediation (i.e. slurry wall and cap), the largest fluctuations occurred within the gravel pit immediately to the west of the disposal area, probably due to the effects from precipitation infiltrating through pervious deposits underlying the base of the pit.

Releases

Types/Causes of Releases--

Demolition debris, domestic refuse, and chemical wastes in the form of liquids and sludges were illegally disposed in a former gravel pit excavation area (unlined). The pit extended into the bedrock, and hazardous constituents were released to the ground water. The contaminated ground-water plume migrated in a northwesterly direction contaminating Lyle Reed Brook and some private residential wells.

Mechanisms for Detection--

In the late 1970s, after reports from nearby residents of heavy odors in Lyle Reed Brook, an area investigation was conducted. Hazardous constituents were subsequently discovered in the brook and in some nearby residential wells. It was determined that the Gilson Road site was the source of this contamination.

Extent of Contamination--

Extensive ground-water contamination exists at the site with the plume extending over an area of 20 acres. Additional contamination exists in Lyle Reed Brook (adjacent to the site). Major hazardous constituents present include methylene chloride, methylethylketone, toluene, benzene, chloroform, tetrahydrofuran, acetone, manganese, nickel, zinc, barium, and arsenic. Sampling and analysis has demonstrated that 800,000 gallons of ground water are currently contaminated with organics. The total amount of organics present in the ground water is estimated to be over 1-million gallons.

Remedial Actions

Response--

In 1980, the State of New Hampshire had approximately 1300 drums removed from the site. The drums were transported to secure landfills in New York and Ohio.

During 1981-1982, a ground-water interception and recirculation system using surface trenches was installed to retard further plume migration. A computer model was used to aid in the design of the interception-recirculation system. Four 8-inch wells were installed near the leading edge of the plume, depressing the water table. The wells formed overlapping cones of depression within the water table, drawing back hazardous constituents from the stream area as well as pumping out upgradient flow. The liquids were pumped back into the ground through the recharge trench. Ground water moving toward the system was diverted by mounding the area around the recharge trench.

In late 1982, a 3 ft thick bentonite-slurry wall was constructed to a maximum depth of approximately 110 ft (average depth to bedrock is 25 ft) in order to key it into the bedrock. A 40 mil polyethylene (impermeable) surface cap was used to cover the entire 20-acre site area. The purpose of the slurry wall and cap was to contain the contaminated ground water while the treatment plant was being built and during the operation of the treatment plant (i.e., until 99% of the hazardous constituents are removed).

In November 1985, construction of a ground-water recovery-treatment-reinjection system will be completed. Treatment includes chemical precipitation (to remove iron and manganese), pH adjustment, sand filtration, air stripping (to remove volatile organics), and an activated sludge system (to remove extractable organics).

The treatment system is designed such that 300 gpm will pass through all phases of treatment except the activated sludge system. Prior to the activated sludge treatment, the waste stream is split; 250 gpm of partially treated ground water will be recirculated back into the ground (for dilution purposes) and 50 gpm will pass through the sludge aeration system to remove extractable organics. Sludge from the metals treatment system and the sludge aeration system are landfilled onsite in two RCRA landfills with a double liner and double leachate collection system. Treated ground water (i.e., water that has passed through the entire treatment system including activated sludge treatment) is reinjected outside the slurry wall to create a negative hydraulic gradient. Ground-water flow is induced back up through the bedrock.

Success/Failure--

The ground-water interception-recirculation system was built with the intent of preventing a major portion of the hazardous constituent plume from reaching Lyle Reed Brook while the more permanent slurry wall was being constructed. Recirculation is tending to homogenize the hazardous constituent concentrations (i.e., eliminating areas of higher concentrations). Since the start of the operation of the recirculation system, the constituent levels in the brook dropped by more than an order of magnitude.

The purpose of the slurry wall and cap were to minimize the infiltration of precipitation to the zone of contamination, to divert ground-water flow around the site, and to slow the advance of the contaminated plume towards

Lyle Reed Brook. The wall was expected to leak somewhat due to the presence of fractures in the bedrock. Also, some of the chemicals in the contaminated aquifer are suspected of being able to degrade bentonite by removing water from the mineral, thus altering the composition of the clay; lab tests do not indicate that this is occurring at the present time (U.S. EPA-MERL in Cincinnati has recently been awarded a research contract to evaluate the bentonite).

The slurry wall is considered to be a "controlled leakage facility". It has been successful in slowing the hazardous constituent plume migration while the treatment plant is being constructed. Some leakage has occurred. However, it is expected that the wall will contain the majority of the hazardous constituents during the treatment operations.

It is too soon to evaluate the effectiveness of the treatment facility. However, the pilot treatment system was able to remove nearly 99 percent of the highly volatile organic compounds by air stripping, and approximately 90 percent of heavy metals by chemical precipitation to metal hydroxides. It is expected that the treatment facility will take 2 to 3 years (approximately 3 complete flushings of the contained area) to reduce the contamination levels in the contained area by 99 percent. The remaining one percent is considered by the New Hampshire Water Supply and Pollution Control Commission, the State of New Hampshire, and the U.S. EPA to be acceptable (acceptable levels were determined by using ACLS).

References: Porter, 1985; Versar, Inc., 1985; GHR Engineering et al., 1981; Knox et al., 1984; Morrison, 1983.

LLANGOLLEN ARMY CREEK LANDFILL - NEW CASTEL, DELAWARE

Facility Description

During the period from 1960 to 1968, the site was used as a landfill by New Castle County for disposal of municipal and industrial wastes. The approximately 47-acre disposal area was located in an abandoned quarry from which 6 to 35 feet of sand and gravel had been removed. Excavation of the area was continued until either the water table or a red-clay zone was encountered. The average depth of the landfill was 25 feet.

In 1970, New Castle County had the landfill covered with sandy material, intending to use the property for a park. The site is currently on the list of Superfund sites.

Site Characteristics

Soils--

The soils in the site area are predominantly sandy soil with some clay. These soils are permeable.

Geology--

The bedrock underlying the site varies in thickness (the landfill was dug through to the aquifer in some places) and is permeable. The landfill lies in the Atlantic Coastal Plain and includes both saturated and unsaturated zones.

Hydrology--

Surface water in the vicinity of the site includes Army Creek, which is adjacent to the site and is currently being contaminated by discharge from recovery wells. Army Creek discharges into the Delaware River located approximately one mile downstream of the site.

Two ground-water aquifers underly the site and are separated by clay; the Columbian and Potomac aquifers. Both aquifers are contaminated. The clay layer separating the aquifers is thin or absent in some areas, thereby allowing hazardous constituents to be passed to the lower aquifer. Pumping from well fields lowered water levels and increased the rate of water movement downward to the lower aquifer.

The Columbian aquifer varies in thickness is located at depths ranging from 10 to 60 ft. The Columbian aquifer consists of surficial sands not thick enough in the immediate area to be developed for water supply. The upper Potomac aquifer, which is located below the Columbian aquifer and ranges in thickness from 2 to 80 ft, is used as a drinking water supply. The maximum depth to the upper Potomac aquifer is 140 ft. The Potomac aquifer overlies Precambrian rocks and consists of silt and clay interbedded with quartz sand and some gravel. The Potomac formation thickens to the southeast and forms one of the most productive confined aquifers in the state. The upper confining layer is thin or absent in areas near and beneath the landfill.

Releases

Types/Causes of Releases--

The leachate from the landfill formed Army Creek and Army Pond. The absence or removal of the red-clay layer in places permitted leachate to migrate into the underlying aquifer. The leachate was not adequately diluted or purified by filtration before it entered the aquifer. Contaminated leachate spread extensively throughout the confined aquifer and began moving toward major public water supply wells. The hazardous constituent plume did reach some private wells in the area.

Mechanisms for Detection--

In 1972, residents of a nearby housing development (Llangollen Heights) reported discoloration of their porcelain fixtures. Sampling and analysis activities were subsequently conducted. A water quality problem was detected in a nearby domestic well.

Currently, there are 58 monitoring wells in the site area to monitor the hazardous constituent plume migration.

Extent of Contamination--

Both the upper and lower ground-water aquifers are contaminated. Surface water adjacent to the site (Army Creek) is currently being contaminated from ground-water pumping activities (recovery wells discharge to Army Creek, which flows into the Delaware River).

Hazardous constituents present at the site include metals (iron, manganese, chromium, beryllium, lead, nickel, zinc, and arsenic), and organic compounds (chloroform, trichloroethylene, and 1,2-dichlorethane). Iron and manganese are the most significant hazardous constituents present at the site.

Remedial Actions

Response--

In 1973, interim measures were undertaken at the Llangollen Army Creek site. Pumping was reduced from the public water supply wells and a program of recovery-well pumping between the landfill and the supply wells was initiated. The pumping system, which continues to operate at the present time, has caused a local cone of depression, which has reduced hazardous constituent movement toward the public water supply wells. Twelve recovery wells have been installed at the site. Most of the recovery wells are screened over 12 to 25 meter intervals and completed 25 to 43 inches below the land surface. The recovery wells discharge into Army Creek (which flows to the Delaware River).

In July 1984, a Consent Order was signed by the responsible party (the County) to do the feasibility study at the site. Remedial measures currently being evaluated include: covering the landfill with a synthetic surface cap, isolating the leachate by installation of a barrier or drainage ditches, removal of refuse and incinerating it or disposing of it at another site, surface grading and runoff control, and relocation of the recovery wells.

Success/Failure--

Interim measures were taken to control migration of the hazardous constituent plume. The feasibility study is being revised at this time (expected completion is in October/November 1985). The hazardous constituent plume is still migrating, but at a slower rate due to the effectiveness of the interim measures implemented.

The direction of flow in the Potomac aquifer has been altered. In the 1960s, flow was to the south and east (after public water supply well fields and industrial well fields were developed). Public water supply wells yield water from depths of 45 to 60 meters (in the confined sand of the Potomac aquifer).

The recovery well system reversed the direction of flow locally away from the supply wells. Flow pattern indicates that water upgradient from the landfill moves through and beneath the landfill where it encounters leachate and is then partially discharged by the recovery wells downgradient from the landfill. Part of the discharge from the recovery wells is uncontaminated ground water from areas south and east of the landfill. Continued pumping for water supply has permitted contaminants to move south of the recovery well system.

References: Bendersky, 1985; Versar, Inc., 1985.

ROCKY MOUNTAIN ARSENAL - NEAR DENVER, COLORADO

Facility Description

The Rocky Mountain Arsenal is an Army facility that, beginning in 1942, was used to manufacture chemical warfare products needed by the U.S. Military. After World War II, portions of the plant were leased to private industry for the manufacture of insecticides and herbicides. During the 1950s, an additional plant was constructed by the Army for the purpose of manufacturing nerve gas.

Liquid wastes from these chemical manufacturing processes were discharged to several unlined surface impoundments resulting in extensive ground-water contamination and some soil contamination. The site is currently listed as a RCRA Superfund site.

Site Characteristics

Topography--

The site is situated on the eastern edge of the broad valley of the South Platte River, east of the foothills of the front range of the Rocky Mountains. The topographic relief across the arsenal site is approximately 200 ft, with a northwest trending slope toward the South Platte River.

Soils--

The soil overburden consists of alluvial sands and gravels interbedded with silt and clay layers. Wind blown sand and silt deposits overlie the alluvium throughout much of the area. The thickness of the overburden ranges from 0 to 100 feet. The overburden in the east and southeast portions of the arsenal site predominantly consists of fine sediments of silty, clayey, fine sands and fine sandy silts. Calcium carbonate cemented zones ranging from a few inches to a few feet thick occur sporadically in the alluvium.

Geology--

The Rocky Mountain Arsenal site lies within the Colorado Piedmont section of the Great Plains physiographic province. The bedrock immediately underlying the site is of the Denver Formation and ranges in thickness from 250 to 400 feet. This Formation consists of deltaic shale, clay stone, sandstone, and occasional conglomerate. The bedrock materials are generally impervious. Occasional thin beds of lignite occur. Fine grained sandstone lenses formed by deltaic channel deposits grade laterally and vertically into shale and claystone.

Hydrology--

The South Platte River is located approximately two miles west of the Rocky Mountain Arsenal site. The general direction of the ground-water movement is to the northwest toward South Platte River. Deviations from the flow pattern occur in the ground water due to variations in the bedrock surface and recharge from isolated ponds, lakes, and streams. Localized direction of ground-water movement is influenced by channelized bedrock surfaces and bedrock highs.

The saturated thickness of the aquifer ranges from 0 to 70 feet, but is irregular and depends upon the configuration of the bedrock surface. The saturated thickness of the bedrock decreases as the bedrock elevation rises. The alluvial aquifer is recharged from the southeast and from infiltrating precipitation within the arsenal site boundaries.

The thickness of the alluvial aquifer in the Northwest Boundary area ranges from 0 to 25 ft. In the Irondale area, the bedrock is 50 to 60 ft deep. Characteristics of the Northwest Boundary aquifer include: transmissivity=210,228 gpd/ft, specific yield=0.085, hydraulic conductivity=1144 ft/day.

Releases

Types/Causes of Releases--

Liquid wastes from the chemical manufacturing processes were disposed in unlined surface impoundments. Hazardous constituents in the wastes included disopropylmethyl phosphate (DIMP), dicyclopentadiene (DCPD), endrin, aldrin, dieldrin, dibromochloropropane (Nemagen), organosulfur compounds, chlorides, and various industrial waste solvents.

Hazardous constituents seeped out of the unlined disposal ponds, infiltrated the underlying alluvial aquifer, and migrated downgradient toward South Platte River. In 1956, an asphalt-lined pond was constructed to hold wastes, but this disposal pond failed to contain the wastes and released hazardous constituents to the underlying ground water aquifer.

Mechanisms for Detection--

The area north of the Arsenal is irrigated. Damage to crops irrigated with shallow ground water was observed during 1950 to 1953. Severe crop damage was reported during 1954, when ground water use was heavier than normal. Several investigations have been conducted since 1954 to determine the cause of the crop damage and to effect a solution. Crop and livestock damages were again reported in 1973 and 1974. Subsequent sampling and analytical data collected by the Colorado Dept. of Health indicated that damages were being caused by ground water contaminated from the Arsenal.

Extent of Contamination--

The extent of ground-water contamination has been defined by 40 monitoring wells installed in 1982. The plume enters the Rocky Mountain Arsenal from the east-southeast and follows a northwest trending buried gully, before exiting the arsenal by taking a northwesterly flow path. A main plume of contaminated ground water extends beyond the northwestern boundary of the Arsenal and a small secondary plume extends beyond the northern boundary of the Arsenal. Hazardous constituents have also been found in several shallow bedrock wells in or near the Arsenal. The areal extent, depth of penetration, and rate of spreading of hazardous constituents in the bedrock have not yet been defined.

Remedial Actions

Response--

Interceptor trenches have been installed in three areas at the site. Wastes from the trenches are collected and treated.

In the North Boundary area, a 6800 ft slurry wall barrier was constructed with dewatering wells located on the southern side of the barrier and recharge wells located on the northern side. The treatment system includes the use of multimedia filters followed by granular carbon adsorbers.

In the Irondale area, a hydraulic barrier was constructed along a 1500 ft line through the use of 30 dewatering wells and 14 reinjection wells. Ground water is pumped to a treatment facility where it is filtered through cartridge filters, adsorbed onto granular carbon, filtered through another set of cartridge filters, and reinjected into the ground. It differs from the north boundary system in that all of the well waters are combined before treatment. Also, the Irondale facility contains larger carbon beds, but less carbon handling equipment.

A similar system of ground-water containment, followed by adsorption treatment and subsequent reinjection of the purified water, has been constructed at the northwest boundary. Three identical parallel treatment trains are located at this boundary. Raw water (from a sump) is pumped through pre-filters with replaceable filter cartridges for the purpose of removing suspended solids (which could interfere with the flow characteristics of the granular activated carbon in the pulse bed adsorber). Adsorbers are in a pulsed bed design operated in the upflow mode similar to the North Boundary and Irondale facilities. Each adsorber contains 1400 cubic feet of carbon which provide a residence time of 21 minutes.

Following carbon treatment, flow from each of the three treatment trains is manifolded together and passed through an on-line tubular post-filter subsystem for removal of carbon fines. The filters are backwashed upon manual or head loss initiation. The treated water is discharged into the treated water sump.

Carbon slurry handling for the removal of spent carbon from and addition of fresh carbon to the pulse bed adsorbers is carried out by a separate subsystem (which includes fresh and spent carbon storage and dual blowcases containing two pressure vessels for each type of carbon).

Success/Failure of Remediation--

The remedial actions implemented at the Rocky Mountain Arsenal site have been successful in preventing contaminated water from exiting the site area. The GAC treatment has decreased the concentrations of DIMP, DBCP, and DCPD to levels below the detection limit. Multi-stage pulsed bed adsorbers, currently employed at all 3 boundary control facilities, have reduced carbon exhaustion rates by 50 percent compared to fixed bed single-stage treatment (originally used at the North Boundary facility).

References: Watensky, 1985; Versar, Inc. 1985; Hager and Loven, 1985; Knox, et al., 1984.

STRINGFELLOW SITE - NEAR RIVERSIDE, CALIFORNIA

Facility Description

The Stringfellow site, located in the Pyrite Canyon (west of Riverside, California), was operated as a licensed Class I toxic industrial waste disposal site between 1956 and 1972. Approximately 32 million gallons of wastes were disposed at the 17-acre site during its period of operation.

The liquid wastes were disposed in several unlined disposal ponds (at one point there were 17 ponds). It was thought that the geology of the canyon area in which the site was located would act as a natural barrier to ground-water contamination. The liquid wastes were concentrated through solar evaporation from the pond surfaces. For a limited period during the operation of the facility, a fountain sprayer was used to enhance evaporation of the wastes. A small concrete barrier (dam) was constructed such that it was keyed into the bedrock at the downstream end of the site. Overflow from the ponds flowed onto the surrounding ground uncontrolled. Fractures in the bedrock formations may have caused releases to the ground water. The site is currently an Enforcement case on the list of Superfund sites.

Site Characteristics

Climate--

The winters between 1977 and 1981 were characterized by abnormally heavy rainfall. Also, heavy storms occurred in March 1969.

Topography--

The site is situated at the head of a small, narrow canyon located in the Jurupa Hills.

Soils--

Alluvium underlies the site area, and ranges in thickness from 45 to greater than 100 feet down the axis of the canyon with an average of about 70 feet. The residuum which lies directly below the alluvium is a weathered portion of the basement complex and is 10 to 30 ft thick; lenses of saturated permeable alluvium were discovered during excavation.

Geology--

The basement complex underlying the alluvium is relatively impermeable and is composed of granite and metamorphic rocks (i.e., two layers lie below the alluvium layer; these are: decomposed or weathered granite and competent or unweathered bedrock). Fractures are present within the basement complex and may provide a means of transport of hazardous constituents to the ground water.

Hydrology--

The ancestral drainage of Pyrite Canyon has two separate branches: the western and the eastern. The current surface drainage pattern corresponds to the western branch. Both drainage patterns contain alluvium. The ancestral eastern stream course passes to the east of the original concrete barrier (dam) and continues down the eastern side of the canyon. The eastern branch may account for the majority of the subsurface flow which currently exists in the site area.

Ground water was discovered at shallow depth within the alluvial deposits downstream of the Stringfellow disposal ponds. Ground-water flow is generally in a southwesterly direction away from the disposal site. Down canyon flow gradients before remedial actions were implemented at the site varied from 0.04 to 0.1 m/m.

Releases

Types/Causes of Releases--

In March 1969 a major storm occurred which caused the waste pond to overflow, inundating the site and causing the release of wastes from the surface impoundment to a nearby creek (Pyrite Creek - normally dry), which resulted in surface contamination of Pyrite Creek for several kilometers downstream.

Additionally, fractures in the bedrock formations underlying the site allowed the release of hazardous constituents to the ground-water beneath the site. Ground-water releases are considered to be the most significant type of hazardous constituent release at this site.

Mechanisms for Detection--

A ground-water monitoring well was located at the mouth of Pyrite Canyon. In 1972, samples from the monitoring well were analyzed. Elevated levels of hexavalent chromium, nitrates, sulfates, and chlorides were indicated, suggesting apparent permit violations. In 1974, the variance permit for operating the facility was revoked by the riverside County Board of Supervisors. Several site investigations have since been conducted in the site area.

Extent of Contamination--

Hazardous constituents present in the ground water include heavy metals, organic halides, and dissolved solids. Although the full extent of contamination is still being investigated, the hazardous constituent plume is known to cover at least a one-mile radius extending downgradient from the site.

As an indication of the levels of organics present in the plume, trichloroethylene has been found in onsite ground water at leves of 15,000 ppb. Analysis of samples collected from the area towards the edge of the one-mile radius plume, have indicated trichloroethylene concentrates of 100 ppb. Other organics such as chlorobenzene, chloroform, and methylene chloride have been found onsite at levels ranging from 700 to 1,700 ppb. Examples of metal concentrations found onsite include: 5,000 ppm aluminum 40 ppm nickel, and 900 ppm iron metals have not been detected in the mid-canyon area (approximately 1,500-2,000 ft downgradient from the site).

Remedial Actions

Response--

Prior to construction of a barrier dam, contaminated materials were excavated by traversing the canyon and cutting completely through to the bedrock. Excavated material was placed in a containment area for neutralization and capping. Ten parts of contaminated materials were mixed with 1 part cement kiln dust (40% CaO) using a mechanical mixer. The mixture was then graded. A six-inch layer of kiln dust, followed by a two-inch layer of packed clay, was spread over the contaminated area to serve as a cap.

A grout curtain was constructed to seal the bedrock under the entire length of the barrier dam. Holes were drilled on 3-ft centers across 800 ft of the canyon in areas of interconnected fractures. A second offset series of grout holes were drilled. A chemical grout was injected via a curtain grouting method using silica-based grout "injectoral". However, fractured areas still remained under certain areas of the curtain.

A clay core barrier and drain was installed upon completion of the grouting. A concrete base was installed at the deepest part of the canyon where liquids would collect. The dimensions of the barrier were: 8 ft wide, 800 ft long, and 25-90 ft deep. The gravel drain, located immediately upstream, is 3 ft thick with a pump located 3 ft from the base to expel collected liquids.

Two interceptor wells were drilled 1800 ft downstream of the site (at what was believed to be the limit of polluted ground water). An additional well was installed 800 ft downstream at the clay barrier to extract more concentrated pollutants before disposal. Wells were greater than 100 ft deep with 6-inch internal diameters. The two southerly wells were able to produce 25 gpm, while the northerly well would only produce 2 gpm. The ability of these wells to sustain these levels is currently being investigated. Two 8,000-gallon tanks were installed onsite for storage of extracted liquids.

Success/Failure--

Monitoring data collected to date does not yet indicate whether or not migration of the hazardous constituent plume has been slowed. Data is not yet available to determine the success or failure of the remediation activites. Determination of the migration rate is difficult because little data exists from before remediation activities took place. Prior to remediation activities, only one monitoring well was in place. Presently, samples are collected from approximately 50 monitoring wells.

References: Ullenberg, 1985; Versar, Inc., 1985.

GULF COASTAL PLAIN SITE

Facility Description

The Gulf Coastal Plain site is a landfill facility used primarily for the disposal of hazardous chemical wastes. Wastewater from a lined storage/evaporation pond was released to a shallow saturated zone when the liner was punctured by construction equipment during a pond cleaning operation.

Site Characteristics

Topography--

The site is located in the Gulf Coastal Plain area. The average land slope in the area is approximately 0.17 percent.

Soils--

The soil material at the site consists of a continuous layer of clay nearly 15 feet in thickness, thinning somewhat in the northwest and southeast portions of the site. The clay material is composed of tan to gray clay and sandy clay with occasional discontinuous sand and clayey sand lenses.

Underlying the surficial clay, is a 20 to 40 ft thick sand layer consisting of silty sand with numerous, thin clay lenses. Field permeability tests indicate permeabilities in the range of 10^{-3} to 10^{-5} cm/sec. A tan, brown and gray clay with thin sand lenses occurs beneath this sand layer. This underlying clay layer ranges from 6 to 15 feet in thickness over the site.

Geology--

The Pleistocene Beaumont Formation, which is composed predominately of clays interbedded with sand layers and lenses, outcrops in the vicinity of the site. These materials were deposited in Pleistocene Deltaic and Fluvial environments and represent distributary channels, interdistributary lakes, bays, and lagoons, as well as river channel and overbank deposits. The Beaumont Formation is underlain by the Lissie Formation which consists of layers of sand, clay, sandstone, and shale. The actual interface between these formations has not been determined due to similarities in the Beaumont Formation and the Upper Lissie Formation.

Hydrology--

Ground water in the site area consists of fresh to slightly saline water and is encountered at depths ranging from 250 to 500 ft. Artesian water in the wells in the vicinity of the site rises to an elevation of 40 to 70 ft below the ground surface. A shallow saturated zone, located in the silty sand layer below the surficial clays, varies in depth from less than 25 ft to more than 30 ft. Non-potable (too saline for use) ground water is contained in this sand layer. Production of water in useable quantities is extremely limited due to the relatively low formation permeabilities. Vertical movement between the layers is limited by the retarding effects of the clays which confine the water-bearing sands. Thus, the flow of contaminated water in the uppermost saturated zone is in a horizontal direction due to the presence of the underlying confining layer.

Recharge to the fresh to slightly saline water zone occurs several miles northwest of the site at the point where the water-bearing sands outcrop. Recharge to the shallow sand occurs off-site to the northwest and southeast of the site where the surficial clays are thinner. Ground-water flows to the site from these areas and exits to the northeast and south.

Releases

Types/Causes of Releases--

The liner of a storage/evaporation pond was punctured by construction equipment during a pond cleaning operation. Leakage of hazardous constituents to the underlying shallow saturated zone subsequently occurred.

Mechanisms for Detection--

Several monitoring wells are located in the site area. Contamination was detected in the shallow saturated zone by site monitoring wells following the puncturing of the liner. Additional monitoring wells were added in both the shallow saturated zone and underlying aquifers to define the extent of contamination.

Extent of Contamination--

Contamination is limited to the uppermost saturated zone in the northeastern portion of the site. The plume remains within the site boundary. Monitoring wells in the deeper aquifers have shown no evidence that contamination has moved downward.

Remedial Actions

Response--

A submersible pump ground-water recovery system using submersible 29 wells was designed and installed. The system was designed to establish a cone of depression in order to contain and eventually remove ground water from the contaminated zone to an evaporation pond.

The submersible pump ground-water recovery system was successful in extracting the anticipated quantities of water. Ground-water contours were altered in a positive fashion but a significant cone of depression that could contain and expedite the removal of contaminated ground-water was not developed. The low yield capacity of the wells was not sufficient to continuously supply the submersible pumps. An engineering evaluation determined that the system would be greatly improved if continuous drawdown at the wells could be maintained.

A ground-water model was used to simulate the effects of various alternatives for ground-water recovery systems. On the basis of the model results, the system selected and constructed was a 500-ft long french drain (form of collector drain) through the long axis of the hazardous constituent plume with one submersible pump at the low end of the drain and five strategically-located wells with jet educator pumps capable of pumping a low-yield well continuously. The french drain consists of a 4-foot by 4-foot gravel drain surrounded by filter cloth and is located at the bottom of the upper sand layer and saturated zone. Jet educator wells were placed in locations outside the zone of influence of the french drain to increase the overall effectiveness of the recovery system. Recharge pits have been placed ahead of the plume of contamination to provide for containment of the plume and reversal of the ground-water flow direction back towards the recovery system. Recharge water is presently being acquired from wells in the deeper aquifers.

A water treatment system is being completed to treat recovered ground water and it is hoped that this treated water may be used for re-injection in recharge pits in the future. Presently, treated ground water is pumped into the site evaporation pond for disposal by evaporation.

Success/Failure of Remediation--

The french drain with eductor wells and recharge pits has produced a higher recovery rate and a more dramatic cone of depression at a faster rate due to a larger surface contact with the saturated zone than can be provided by individual wells, a zone of high permeability which essentially forms a long lateral well, and the allowance for continuous pumping. The actual pumping rate has exceeded the predicted pumping rate by nearly 30 percent.

Monthly monitoring data is collected from the facility monitoring wells. Current data shows that the plume has decreased in size and concentration due to the operation of the system. In the three years that the recovery system has been in operation, the areal extent of th plume of contamination has decreased by approximately 50 percent. Results to this point in time indicate that this combination recovery system can be used in various soils of relatively low permeability; i.e., soils in the fine sand to silt ranges with permeabilities too low to support continuous pumping with conventional submersible pump recovery systems.

Reference: Underwood, 1985.

WHITMOYER LABORATORIES - MYERSTOWN, PENNSYLVANIA

Facility Description

Beginning in 1934 and continuing to the present, Whitmoyer Laboratories operated a pharmaceutical manufacturing facility at the site. Wastewater generated by the manufacturing processes was treated with lime and handled as a slurry. The wastewater slurry was then disposed in an unlined lagoon.

Site Description

Climate--

The average annual precipitation in the site area is 44 inches. Average annual snowfall is 35 inches. Average temperatures range from 30°F (July) to 76°F (January) with an annual average of 53°F. The average windspeed is 7.7 mph.

Soils--

Soils overlying the site consist of a 5 to 7 ft thick layer of alluvial sand, silt, and gravels. These soils are fairly permeable, and allow for rapid recharge to the bedrock aquifers.

Geology--

Bedrock underlying the plant site consists of limestones and dolomites which strike east-northeast and exhibit a dip of 30 degrees to the southeast [Ontelaunee Formation (dolomite) = 900 feet thick; underlying Annville Formation (high calcium limestone) = 1500 ft north of the plant]

Hydrology--

The site lies adjacent to Tulpehocken Creek (37 miles upstream from its confluence with the Schuylkill River, which in turn flows to Delaware Bay). The drainage basin of Tulpehocken Creek covers 211 square miles and is 33.5 miles long. The average and minimum flows at the confluence of Schuylkill River are 58 cfs and 56 cfs, respectively. The average annual flow for the creek is approximately 200 cfs and the maximum flood flow was 9890 cfs (on December 7, 1953). The creek flows east-northeast (following the strike of the carbonate bedrock).

Ground water beneath the site is potable and is used by local residents and farmers. There are some artesian wells near the site, but the static water level in most wells lies near the ground-water table. The site lies close to a ground-water divide in a system of limestone aquifers underlying the Lebanon Valley.

Releases

Types/Causes of Releases--

Improper waste disposal in an unlined surface impoundment (lagoon) caused releases to ground-water underlying the site, soils onsite, and a nearby stream (Tulpehocken Creek).

Mechanisms for Detection--

In July 1964, Whitmoyer Laboratories, Inc. became a subsidiary of Rohm and Haas Company. Extensive arsenic contamination of the soils, ground-water, and a nearby stream became apparent to Rohm and Haas Company officials during an inspection of the facility.

Extent of Contamination--

Extensive ground-water, soils, and surface water contamination exists in the site area. Hazardous constituents primarily include organically bound arsenic compounds, calcium arsenate, and calcuim arsenite.

Remedial Actions

Response Actions--

Onsite treatment and disposal practices were discontinued in December 1964. Sludge was removed from the lagoon. Contaminated soils underlying the lagoon were also removed. The contaminated soil and sludge materials were deposited in an impervious concrete storage bin, which was filled to capacity and then covered.

Four recovery wells were used to purge ground-water containing arsenic compounds. The contaminated ground-water was treated by adding 2 parts $Fe_2(SO_4)_3$ to 1 part arsenic and adjusting the pH to neutral conditions (by adding lime). Recovered water was handled in alternating batch mixing tanks on a continuous feed treatment schedule and sent to the lagoons to dissipate via slow percolation to the subsoil.

The plant reopened in the spring of 1965 on a no-discharge basis. Treated wastes were trucked to a New Jersey holding area awaiting ocean dumping.

In 1966, additional wells were installed. Production wells formed cones of depression east of the plant to stop migration of ground-water. Production rate is partially dependent on the purging rate. From 1968 to early 1971, the purged water was discharged directly to Tulpehocken Creek.

It was decided that it would be too expensive to dredge Tulpehocken Creek, and the hazardous constituent levels are declining through dilution. Whitmoyer Laboratories currently supplies bottled water to area residents whose wells remain affected.

Success/Failure of Remediation--

The first phase of remedial action cleanup and recovery involved the removal of sludge and contaminated soils. The manufacturing processes were halted until a process could be developed to remove arsenic from the wastewater, thereby eleiminating the possiblity of new arsenic compounds being added to the soils and subsequently to the ground and suface water.

The next phase, which involved removal of the arsenic hazardous constituents from the ground-water, was also successful. The recycling and treatment of the purged water did reduce the level of arsenic in the ground-water, and succeeded in controlling its movement.

Little has been done to remove the hazardous constituents from the sediments and surface water of Tulpehocken Creek, because of the costs involved in dredging miles of creek bottoms and banks. Through dilution, the arsenic levels in the creek water have been brought within the limits set by the U.S. Department of Health, and monitoring has shown that the levels continue to decline. Whitmoyer Laboratories supplies bottled water to those area residents whose wells remain affected.

Finally, routine monitoring of the site is being performed to ensure that the arsenic levels do not increase, either through the release of arsenic from bottom muds, or via spills from the plant.

References: EPA, 1981.

SECTION 4

RECOMMENDATIONS FOR SELECTING AND IMPLEMENTING CORRECTIVE MEASURES FOR RELEASES TO GROUND WATER

OVERVIEW

As previously discussed in Section 2, before a suitable corrective measure can be selected for remediation of contaminated ground water, the need for such a corrective measure must be determined. A corrective measure for ground-water release is required when concentrations of HCs, measured at the point of compliance, exceed either background constituent levels, the maximum concentration for parameters in Table 1 of 40 CFR Part 264.94, or an ACL. After identifying a need, the most appropriate corrective measure(s) for the site in question must be selected and subsequently implemented. Section 2 identified, hydrogeologic control/treatment technologies and specific treatment technologies applicable to the remediation of contaminated ground water so that the requirements of 40 CFR Part 264.100(b) are met. Table 2.13 indicates the proven, imminent and emerging control/treatment technologies which may be used to treat, remove or control contaminated ground-water such that the threat to human health or the environment is mitigated or eliminated. Table 2.14 presents technologies applicable to the treatment of contaminated ground water upon removal from the subsurface. These control and treatment technologies are assessed according to their applicability in certain hydrogeologic conditions, their compatibility with specific wastes, their effectiveness in contaminated ground-water control, removal and treatment and their technical, environmental and institutional suitability. As is evident from Section 2, "Overview of Corrective measures for Releases to Ground Water", there are many technologies that may be selected that are capable of or potentially capable of treating or controlling ground-water contamination. However, to ensure that the most appropriate technology(s) is selected for implementation at a site, available technologies must be assessed according to their site applicability, waste compatibility, effectivenesss and reliability.

SELECTION PROCESS

When a ground-water release has been detected, or suspected to have occurred, as evidenced by a preliminary site assessment, and a corrective measures deemed necessary, the most appropriate (technically, environmentally etc.) corrective measure(s) must be selected. This requires that the applicant perform a logical progression of decision making processes. These are:

- adequate site/hydrogeologic investigation;
- screening;
- selection;
- recommedations;
- implementation; and
- monitoring.

This progression should also be followed by the permit writer to ensure that the applicant has considered all available corrective measures and has selected the one(s) most appropriate to the site in question.

Site Investigation

After a preliminary site assessment indicates that a release has occurred and that the release is a potential hazard to human health and the environment, a thorough site investigation is necessary to determine specific site characteristics. The permit writer must examine the available data submitted by the applicant and decide upon the adequacy of the site investigation with respect to selecting an appropriate corrective measure for remediation. The permit writer should identify any data gaps that may affect the final selected action. The following must be properly characterized:

- waste characteristics (type, toxicity, migration potential);
- extent of contamination (fate and transport, potential receptors, concentration);
- ground water, surface water and soil characteristics (location, type, flow rate, permeability, hydraulic gradient, pH);
- site location (proximity to local populations and ground-water supplies, climate); and
- hydrogeology (bedrock location, fracturing, jointing, depth to water table).

These parameters will determine the migration potential of hazardous constituents and their potential environmental impact, and will greatly influence the selection of an appropriate corrective measure and its final engineering design. Many of the characteristics needed to be identified may already be available through previous site investigations which should be used as a base-line for any further investigation.

Section 2 ("Hydrogeologic Approaches" subsection) indicates the type of site/hydrogeologic information that should be provided for the implementation of the control/treatment technologies. Additionally, it provides a general permit writers' checklist identifying the site soil, ground water, aquifer and hazardous constituent plume characteristics which should be provided from a site investigation.

Screening

The initial step in the screening process is the development of general response objectives to identify the goals and extent of the corrective measure to be used. The site investigation should identify the possible receptors. Corrective measures to mitigate or eliminate the threat posed to these receptors can then be formulated.

All potential remedial technologies should be gathered for consideration and assessed according to their technical and environmental suitability to the site in question. Applicable federal, state and local laws; technology effectiveness, reliability, waste compatibility, site applicability/effectiveness and relative cost; and potential environmental and public health impacts due to the implementation of the corrective measure should be considered in the screening process.

Selection

From the site investigation and the screening process a final decision concerning the most applicable corrective measure must be made. The permit writer must review all aspects of the applicant's report including the completeness of the site investigation. As previously stated, much of the site investigation material may be readily available from other reports performed at the site; however, the permit writer must ensure that further investigations have properly characterized all parameters that may affect the release and corrective measure used.

From the technology screening, the applicant should arrive at the most appropriate measure for remediation. The permit writer should be certain that the measure is adequately focused on the risk posed by the contaminant release; i.e., that the endangerment or risk to human health and the environment is mitigated/eliminated by the corrective action(s).

If the permit writer does not believe the applicant has properly addressed the issues in the site investigation and screening process, then the applicant should not implement the proposed corrective action plan. At this point the permit writer may convey to the applicant any shortcomings evident in the site investigation or thought process in obtaining the corrective measue.

The permit writer may also suggest to the applicant other measures that he or she feels may be more applicable to the given situation. This could possibly involve pilot studies to evaluate the overall performance and effectiveness of a selected measure. These types of studies can be very valuable in recommending and selecting the appropriate corrective measures for site remediation.

Conceptual Design

Once the corrective measure(s) has been chosen, a detailed conceptual design can be developed. Upon completion (and approval), implementation of the corrective measure can proceed.

Some important activities must be carried out during the implementation of the measure. These include field inspections to ensure quality control during construction, and to ensure that design specifications for construction and materials are being adhered to. Any alteration that occurs during construction must be investigated by a certified engineer to determine if it will affect the performance fo the corrective measure. These inspections during implementation must include monitoring to determine that contaminated ground water is being properly treated (i.e. to appropriate levels) or if being removed, that it is being disposed of and/or transported in an acceptable manner. These monitoring and inspection activities are very important to ensure that the corrective measure(s) will perform as designed.

Monitoring

Upon completion of the corrective measure, a monitoring plan must be initiated to ensure that the corrective measure has been properly installed and is performing as specified. If failure or only partial success occurs, then monitoring can be used to determine what further type of remediation may be necessary.

Monitoring can be done in both the upgradient and downgradient ground water through the use of monitoring wells to reveal if contamination is continuing to migrate into the ground-water. Lysimeters can also be used to monitor the unsaturated zone for hazardous constituent concentration and migration.

USE OF SUMMARY TABLES

Table 4.1, is presented to assist the permit writer in reviewing applications for correcting releases to ground water. This table illustrates the types of control/treatment and treatment (after removal from subsurface) technologies applicable to remediation of contaminated ground water and the

TABLE 4.1. SUMMARY OF GROUND-WATER CONTROL/TREATMENT AND TREATMENT TECHNOLOGIES

Control/Treatment Strategies		Control/Treatment Categories/Technologies[a]												Treatment Technologies[b]																					Effectiveness/Comments[c]
		Impermeable Barriers				Well Systems			Subsurface Drains		In Situ Treatment																								
Control	Control/ Treatment	Slurry Cut-Off Wall	Grout Curtain	Sheet Pile Cut-Off Wall	Block Displacement Method	Well Point Systems	Deep Well Systems	Recharge Systems	Collector Drains	Interceptor Trenches	Permeable Treatment Bed	Chemical Injection	Bioreclamation	Air Stripping*	Carbon Adsorption*	Chemical Oxidation*	Chemical Reduction	Distillation	Electrodialysis	Electrolysis	Evaporation	Filtration*	Flocculation	Hydrolysis	Ion Exchange*	Liquid Ion Exchange	Neutralization	Ozonation	Precipitation	Resin Adsorption	Reverse Osmosis*	Sedimentation	Steam Stripping	Ultrafiltration	
Upgradient ground-water diversion		X	X	X	X	X	X	X	X	X																									Not effective in meeting the requirements of 40 CFR Part 264.100(b) alone, requires additional remedial measures such as ground-water pumping and treatment.
	Downgradient ground-water diversion/ interception	X		X	X	X	X	X	X	X	X			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	Meets requirements of 40 CFR Part 264.100(b) in that it provides for removal and treatment of contaminated ground water.
	Extraction/ recharge					X	X	X					X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	Includes the removal of contaminated ground water and may include the treatment of extracted ground water for subsequent recharge.
	In-situ treatment										X	X	X																						Meets the requirements of 40 CFR Part 264.100(b).

[a] Control/treatment technologies, as discussed in Section 2 (Hydrogeologic Approaches subsection), are those techniques which can be applied directly to the subsurface for containment, removal and/or treatment of contaminated ground water.

[b] Treatment technologies, as discussed in Section 2 (Treatment Technologies subsection), are those technologies which can be applied to treat contaminated ground water after removal from the subsurface.

[c] Note that the effectiveness of control/treatment and treatment technologies depends on several factors, as discussed in Section 2, particularly hydrogeologic and hazardous constituent characteristics.

*Most commonly used technologies for the treatment of contaminated ground water.

relative location and effectiveness of these technologies, as discussed in the body of this guidance document. Table 4.1 was developed from detailed technology discussions provided in Section 2 and case studies, presented in Section 3, indicating the site applicability and success/failure of corrective measures at the sites studied. The usefulness of this table can be illustrated by evaluating, in detail, one of these case studies.

Additionally, a table (Table 4.2) summarizing source control corrective measures has been provided to further assist the permit writer in application review.

CASE STUDY EXAMPLE

Consider the Gilson Road, Nashua, New Hampshire site. By reviewing the technology discussions/data requirements provided in Section 2 and by completing the Permit Writers' Checklist, as shown, the applicability of the corrective measures implemented at this site can be assessed.

Site hydrogeologic information could be more extensive, however the primary soil/ground-water/aquifer/hazardous constituent plume characteristics have been addressed. As elaborated upon in the case study discussion, in 1980 source control remedial measures were undertaken. During 1981-82, a ground-water interception and recirculation system using subsurface drains (i.e., interceptor trenches) and well systems for extraction/recharge were installed to retard plume migration. In late 1982, a bentonite-slurry wall was constructed and keyed into the bedrock and a cap was installed to cover the entire site area so that contaminated ground water could be temporarily contained until a recovery-treatment-reinjection plant/system is constructed (construction to be completed in November 1985). Treatment technologies include chemical precipitation, pH adjustment, filtration, air stripping and an activated sludge system.

As indicated on the subsequent completed Permit Writers' Checklist, for the Gilson Road site, the slurry wall was a satisfactory temporary technology for control of plume migration while the treatment facility was being completed. However, due to the presence of bedrock fractures and the potential hazardous constituent/slurry wall incompatibility

TABLE 4.2. SOURCE CONTROL CORRECTIVE MEASURES FOR DIRECT AND INDIRECT RELEASES TO GROUND WATER

		Appropriate Corrective Actions										
Facility Type/ Nature of Release	Response Strategy	Removal	Grading	Capping	Diversion/Collection	Revegetation	Site Management	Maintenance	Redesign	Reconstruct	Effectiveness	Comments
Landfills/Waste Piles												
Failure of liner/leachate collection system resulting in the release of leachate to ground and surface waters	Enhance capability of system							X	X	X	Dependent on extent of problems, original design, and amount of overburden.	Likely to be costly and may require excavation of landfill, secondary containment may be needed.
			X	X	X		X				Applicable for reducing runon and infiltration. May not affect subsurface water movement.	
Release of contaminated runoff resulting from precipitation and/or runon contacting waste	Prevent surface water from contacting waste		X		X		X				Movement of surface water is an effective method of reducing the volume of contaminated water.	Surface water management erosion control and maintaining cover material are most effective when used in conjunction with each other.
	Cover waste			X		X	X				Reduces infiltration of precipitation thereby reducing generation of leachate.	
Erosion of cover resulting in waste and contaminated soils being transported from site	Erosion control		X			X					Effective for gentle slopes.	
	Run-on control		X		X						Effective in reducing threat of erosion.	
Washout of landfill by streams or floodwaters	Restore facility integrity and prevent future occurrences			X	X	X				X	Effective if site hydrogeologic characteristics are considered.	

(continued)

TABLE 4.2 (continued)

Facility Type/ Nature of Release	Response Strategy	Appropriate Corrective Actions									Effectiveness	Comments
		Removal	Grading	Capping	Diversion/Collection	Revegetation	Site Management	Maintenance	Redesign	Reconstruct		
Surface Impoundments												
Overtopping of dikes resulting in release of wastes and/or contaminated runoff	Reduce run-on		X	X	X						Effective if the cause of overtopping is excessive run-on.	Management of wastes and surface waters must focus on the areas balance of liquids in relation to impoundment capacity.
	Add freeboard to dikes to increase impoundment capacity								X	X	Not likely to be effective except for additional short-term storage.	
	Increase freeboard by lowering impoundment elevation	X					X				Likely to be effective only on a temporary basis.	
Seepage of contaminated liquids through containment dikes due to cracks or excessive permeability	Repair cracks in dikes						X	X		X	Dependent upon cause of cracks and quality of repair work and maintenance.	Seepage control measures include liners, solid barriers (steel), injected barriers (cement), and reconstruction with impermeable soils.
	Eliminate seepage due to high permeability materials used in construction			X					X	X	Variable depending on technology employed and quality of installation.	
Dike failure and wash-out due to overtopping, erosion, or slope failure	Replacement of dike and prevention of reoccurences		X						X	X	To be effective, replacement must include an evaluation of the cause(s) of dike failure and be reflected in the design of new dikes.	

(continued)

TABLE 4.2 (continued)

Facility Type/ Nature of Release	Response Strategy	Appropriate Corrective Actions: Removal	Grading	Capping	Diversion/Collection	Revegetation	Site Management	Maintenance	Redesign	Reconstruct	Effectiveness	Comments
Tanks												
Release of liquid wastes due to structural failure of tank	Decommission irreparable tanks and replace with new tanks	X	X			X					Removal of wastes and cleaning tank will preclude future releases.	Tank removal will depend on the size and material of the tank. Steel may be recyclable, concrete may be demolished and graded or disposed of off-site.
	Repair tank	X					X			X	Effective repair will likely require waste removal. Repair must consider overall condition of tank and compatibility of tank material, repair material and waste types.	
Release of waste due to tank overflow or spills during transfer operations	Improve facility management and develop secondary containment					X	X		X	X	Requires commitment by facility operator to reduce chance of spills. Secondary containment must be adequately sized.	Site management should include gauges, worker training and locked valves.
Release of contaminated runoff	Prevent runon from contacting waste		X		X		X				Run-on control must be combined with facility management to confine waste to tanks.	
	Keep site free of uncontaminated waste	X					X				Secondary containment areas should be maintained free of hazardous constituents.	

(continued)

TABLE 4.2 (continued)

Facility Type/ Nature of Release	Response Strategy	Appropriate Corrective Actions									Effectiveness	Comments
		Removal	Grading	Capping	Diversion/Collection	Revegetation	Site Management	Maintenance	Redesign	Reconstruct		
Waste Handling and Container Storage Areas and Incinerators												
Release of waste from leaking containers	Replace or overpack leaking containers	X					X	X			Effective in reducing threat of future releases.	Releases from storage and handling facilities are best controlled by preventing releases and by ensuring that adequate secondary containment facilities are in place.
	Develop secondary containment								X	X	Effective in confining releases to the facility.	
Release of contaminated run-on and/or precipitation	Prevent run-on from contacting waste		X		X		X		X	X	Surface water management can prevent run-on, waste management should ensure that any precipitation or run-on which contacts waste does not leave the site.	
Spills of waste during handling operations	Improve handling procedures						X				Focus on employee training and awareness and on appropriateness of equipment. Effectiveness difficult to measure.	
	Develop secondary containment						X		X	X	Effective in confining releases.	

SOURCE: E.C. Jordan, 1985

PERMIT WRITERS' CHECKLIST

Site Name/Location Gilson Road New Hampshire Site

1. Has applicant undertaken a hydrogeologic investigation of the site in question? (yes or no) yes

2. Does hydrogeologic investigation include the following information (place check beside data provided):

Site Soil Characteristics

• Type	X
• Texture (granular or cohesive)	X
• Grain size distribution and gradation	X
• Moisture content	
• Permeability	X
• Soil pressure	
• Porosity	
• Composition	
• Compaction	X
• Discontinuities in soil strate (e.g. fault)	X
• Cohesive and consolidation states of individual strata	
• Degree and orientation of soil stratification and bedding	X
• Location and type of weathered bedrock or solution channels	X
• Other (specify)	

Ground-Water Characteristics

• Depth to water table	X
• Direction of flow	X
• Rate of flow	X
• pH	
• Hardness	
• Salt concentration	
• Presence of minerals and organics	

- Concentration of sulfides and calcium ____
- Water pressure ____
- Recharge quantity ____
- Location of neighboring water bodies (e.g. streams) X
- Other (specify) ____

Aquifer Characteristics

- Use of aquifer ____
- Permeability and thickness of water bearing strata X
- Transmissivity ____
- Storativity ____
- Specific yield ____
- Depth X
- Type (confined or unconfined) X
- Condition (e.g. homogeneous, isotropic, leaky) ____
- Hydraulic gradient ____
- Effective porosity ____
- Identification of recharge and discharge areas ____
- Identification of aquifer boundaries (i.e. areal extent) X
- Aquiclude characteristics (depth, permeability, degree of jointing, hardness, continuity) ____
- Other (specifiy) ____

Hazardous Constituent Plume Characteristics

- Size X
- Location X
- Shape ____
- Hydraulic gradient across plume ____
- Depth to plume X
- Chemistry and concentration X
- Velocity ____
- Other (specify) ____

3. Indicate ground-water control/treatment technology under consideration by applicant (specify particular technology(s) beside appropriate category):

- Impermeable barrier X
- Well system X
- Interceptor system or subsurface drain X
- In situ treatment

4. Control/treatment technology(s) strategy and location: (check strategy/location and indicate number of control/treatment units)

- Upgradient diversion
- Downgradient diversion/interception X
- Surrounding site
- Extraction/recharge X
- In situ treatment

(• Source control X)

5. Purpose of control/treatment technology: (check appropriate purpose(s))

- Control ground-water flow X
- Treat ground-water X
- Isolate hazardous constituent plume X
- Extract hazardous constituent plume X
- Replenish ground-water X
- Adjust water table
- Control subsurface flow of hazardous constituents X
- Neutralize, precipitate or destroy hazardous constituents
- Other (specify) Cap to minimize infiltration of precipitation

6. Is control/treatment technology applicable to site terms of: (yes or no; refer to appropriate control/treatment technology discussions).

• Implementability	
• Effectiveness	yes
• Reliability	
• Compatability of hazardous constituent plume with technology	yes (as temporary measure)
• Site's subsurface characteristics	yes (as temporary measure but additional measures i.e., grouting could be implemented)

7. Environmental concerns associated with this control/treatment technology: (check where applicable)

• Subsidence	X
• Decrease in well yield of adjacent well fluid	
• Drawdown of adjacent surface water bodies	X
• Induced hazardous constituent migration to new pathways	
• Other (specify)	

the wall leaked and was expected to leak to some degree. Although the technologies implemented at this site were successful in minimizing hazardous constituent migration, with the use of additional technologies, such as grouting to seal the bedrock fractures, the effectiveness of corrective measures at the site could be further improved. By referring to Table 4.1 it is evident that the slurry wall, well system, and interceptor trench corrective measures and treatment technologies implemented at the site for remediation of contaminated ground water are appropriate. For further verification refer to Tables 2.13 and 2.14 which discuss hydrogeologic and hazardous constituent applicability of control/treatment and treatment technologies, respectively.

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APPENDIX A

UNDERGROUND INJECTION: CLASS I AND IV WELLS

INTRODUCTION

Class I and IV underground injection wells are considered land-based solid waste management units (SWMUs). Due to the unique operating conditions and regulatory management of Class I and IV wells, it is worthwhile to discuss Class I and IV wells separately.

DEFINITIONS OF CLASS I AND IV WELLS

Class I underground injection wells, commonly referred to as deep wells, are defined as follows (40 CFR 144.6(a)):

1. Wells used by generators of hazardous waste or owners or operators of hazardous waste management facilties to inject hazardous waste beneath the lowermost formation containing, within one-quarter mile of the well bore, an underground source of drinking water (USDW);
2. Other industrial and municipal disposal wells which inject fluids beneath the lowermost formation containing, within one-quarter mile of the well bore, an USDW.

Class IV underground injection wells are defined as follows (40 CFR 144.6(d)):

1. Wells used by generators of hazardous waste or of radioactive waste, by owners or operators of hazardous waste management facilities or by owners or operators of radioactive waste disposal sites to dispose of hazardous waste or radioactive waste into a formation which within one-quarter mile of the well contains an USDW;
2. Wells used by generators of hazardous waste or of radioactive waste, by owners or operators of hazardous waste management facilities, or by owners or operators of radioactive waste disposal sites to

dispose of hazardous waste or radioactive waste above a formation which within one-quarter mile of the well contains an USDW; or

3. Wells used by generators of hazardous waste or owners or operators of hazardous waste management facilities to dispose of hazardous waste, which cannot be classified under item 1 of the definition of a Class I well or under items 1 and 2 of the Class IV well definition (see above definitions). Included but not limited to this definition are wells used to dispose of hazardous waste into or above a formation which contains an aquifer which has been exempted pursuant to 40 CFR 146.04--criteria for exempted aquifers. In general, an aquifer is exempted if it does not serve as a source of drinking water and it cannot now and will not in the future serve as a source of drinking water; or the total dissolved solids (TDS) content of the ground water is between 3,000 and 10,000 mg/L and it is not expected to supply a public water system.

Class I and IV wells are the only wells that inject hazardous waste. The major difference between Class I and Class IV wells, as noted in the above definitions, is the depth and loction of injection; Class IV wells having the shallowest injection depth one-quarter mile above an USDW. The remaining injection wells include oil and gas production and storage wells and enhanced recovery wells (Class II), mineral mining wells (e.g., in situ production of metals, sulfur mining and solution mining--Class III), and injection wells not included in the definitions of Class I, II, III, or IV wells (Class V).

REGULATORY FRAMEWORK

Underground injection wells fall under the jurisdiction of the Federal Safe Drinking Water Act (SDWA), Public Law 95-523, as amended. Part C of the SDWA provides for the protection of USDWs through federal guidelines and regulations and the administration of regulatory programs at the state level. USDWs are defined as all aquifers containing water with less than 10,000 mg/L total dissolved solids (TDS). The Federal Underground Injection Control (UIC) Program appears at 40 CFR Parts 144 through 146. Part 144 contains permit information and conditions, and financial responsibility. Part 145 contains the State UIC Program requirements. Part 146 includes the UIC technical regulations. Underground injection of hazardous waste is also regulated under the Resource Conservation and Recovery Act of 1976 (RCRA). RCRA, however, is only applicable when hazardous waste is being injected without a UIC permit or in the absence of an authorized program. The National Pollutant Discharge

Elimination System (NPDES) under the Federal Clean Water Act (CWA) has little authority over the actual injection of wastes underground, except where a navigable body of water is receiving injected wastes.

Class IV wells have recently been banned and are required to be plugged and abandoned six months after the UIC program becomes effective in a state, 40 CFR 144.23(c) (December 1984 for most states and June 1985 for the remaining states). Section 405 of the Hazardous and Solid Waste Amendments of 1984 has reinforced the ban by prohibiting the disposal of hazardous waste by underground injection into or above an USDW on May 8, 1985 (RCRA, Section 7010). Most states have already banned the use of Class IV wells, and when Class IV wells are identified in those states they are shut down.

CURRENT STATUS

Data on Class I and limited data on Class IV wells have been compiled by the EPA Office of Drinking Water in a report entitled "Report to Congress on Injection of Hazardous Waste," signed and released May 1985 (herein referred to as EPA/ODW, 1985). The banning of Class IV wells on the state and federal levels has limited the use of Class IV wells and has, therefore, limited the information available on Class IV injection practices. EPA is currently focusing their effort on proper closure and monitoring of these wells to detect and prevent any contamination to an USDW.

Although the Hazardous and Solid Waste Amendments of 1984 may place future restrictions on the types of wastes available for injection and location of new wells, the injection of hazardous waste into Class I wells remains an active practice. As of March 18, 1985, 32 states had applied for and received enforcement authority of the UIC program for Class I hazardous waste wells. EPA has promulgated 25 programs in states that chose not to or did not obtain delegation of the UIC program for Class I wells.

Active hazardous waste injection wells are found in 15 states. A majority of the wells are located along the Gulf Coast and near the Great Lakes with 66 percent of the wells concentrated in Louisiana and Texas. These two regions have a history of underground injection in the area of oil and gas production activities and, therefore, have abundant data on geologic formations. These regions also possess suitable geologic formations for efficient injection.

The EPA/ODW 1985 report revealed information on 34 Class IV wells located in 12 states. Sixteen of these wells have been permanently plugged and abandoned; 11 wells are in the closure process (i.e., abandoned but not yet plugged). Four wells were active and under investigation as of March 1985; and three wells, one of which is plugged, are designated CERCLA sites. The EPA/ODW report identified 112 facilities which inject hazardous waste through 252 Class I wells. Ninety of these facilities were active and injected hazardous waste into 195 wells during 1984 (only 181 wells were operating in 1983). The remaining 57 wells (out of 252) were inactive. Of the 195 active wells, 152 operated continuously and 43 intermittently. Of the 57 inactive wells, 41 were abandoned, 3 were shut-in or in the process of changing type of operating, and 13 had a permit pending or were under construction.

GROUND WATER CONTAMINATION FROM UNDERGROUND INJECTION

Five basic pathways have been identified in which injection practices can cause fluids to migrate into an USDW (EPA/ODW, 1985):

1. Faulty wall construction (i.e., leaks in well casing);
2. Improperly plugged or completed wells in the zone of endangering influence;
3. Faulty or fractured confining strata (i.e., due to improper injection pressure used and injection into or below an inadequate confining formation);
4. Lateral displacement (i.e., due to inproper injection pressures and inadequate detection of faults and recharge areas); and
5. Direct injection (i.e., injection into or above USDWs which is currently banned by EPA).

The technical requirements of the UIC regulations (40 CFR Part 146) are designed to address the pathways of migration stated above. Proper construction of Class I wells is required at 40 CFR 146.12. Mechanical integrity tests (MITs) for Class I wells are required prior to initial injection and every five years thereafter to confirm the integrity of the well's construction (40 CFR Part 146.08). The use of MITs has proved to be an excellent device in identifying defects and preventing contamination before any damage is done. The proper operation and continuous monitoring and reporting of the volume and the injection and annulus pressure, required at 40 CFR Part 146.13, provides information on the operation of wells. If detection of fluid migration from the well occurs, corrective action is required (40 CFR Part 144.55 and 146.07). In addition, financial requirements for Class I wells (40 CFR 144 Subpart F) assure financial liability and responsibility for those wells for present and future problems. Proper plugging and abandonment, required by 40 CFR Part 146.10 and 144.23, reduces the possiblity of future contamination from the well.

Due to the location of Class IV wells, it can be assumed in most cases that hazardous waste or constituents will reach or have reached the uppermost aquifer. This fact alone has provided grounds for the ban on use of Class IV wells. However, the shallow depth of Class IV wells (maximum depth of 1,000 ft) does allow for the use of monitoring wells to determine and identify if any release/migration of fluids from the well has occurred. Conversely, the detection of fluid migration from Class I wells presents a problem. The average depth of a Class I well ranges from 1,000 to 5,000 ft. Some wells are documented with a depth of up to 7,000 ft. There are concerns about drilling a monitoring well this deep. The monitoring well could possibly serve as a conduit for the rise of injected wastes into useable aquifers at some point in the future. There is no current technology to properly locate a well for this purpose because it may take hundreds to thousands of years to detect a release from the injected zone. These monitoring wells are also difficult and expensive to construct and operate. Presently, only a few deep aquifers associated with Class I wells are being monitored. Some proponents of Class I wells argue that if Class I wells are located in sound geologic areas and are constructed and operated properly there should be few problems with contamination of USDWs. Supporting data indicates that deep well injection occurs in and below aquifers that contain very high volumes of TDS which are too great to have any potential for human use now or in the future.

Currently, few documented cases exist in which contamination of an USDW has occurred from underground injection practices. This may partly be the result of the limited practice of underground injection. Enforcement information collected by the Office of Drinking Water (EPA/ODW, 1985) revealed that out of a reported 84 noncompliance incidents at 39 facilities, administrative violations accounted for 50 percent (42 incidents) and construction, design, or operational problems accounted for the remaining 50 percent. Of the 42 nonadministrative violations, legal action was only required in 10 cases. Of all the violations only nine cases presented significant problems which could have resulted in the contamination of USDWs. Of these nine cases only three cases of USDW contamination have been documented. Migration from the wells eventually causing USDW contamination occurred from excessive injection pressures, the injection of incompatible wastes, the injection of wastes with a lower pH than authorized, and inadequate operator training. One of these sites is now a Superfund site and is scheduled for remedial action. Current documented corrective measures employed at these sites include plugging the wells, using recovery wells and reinjecting into the permitted zones through new wells, and pumping out contaminated water.

Preventative measures are currently being employed at some facilities with Class I wells. Examples of these measures include pretreating the waste prior to injection, avoiding the injection of incompatible waste streams, installing automatic shutoff systems which stop injection when certain monitored parameters reach specific levels, and installing special operating techiques to prevent well blowouts. In addition, the implementation of proper closure techniques to plug and abandon wells as well as proper monitoring prior to and following closure remain the important techniques in detecting releases and preventing contamination to USDWs.

REFERENCES FOR APPENDIX A

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